DROUGHT IN HAWAIʻI

Report R88

State of Hawaii
DEPARTMENT OF LAND AND NATURAL RESOURCES
Commission on Water Resource Management

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ABSTRACT

This report describes an investigation of the spatial distribution, frequency, duration, intensity, and impacts of historical droughts in Hawai‘i and demonstrates the utility of this information for short- and long-term drought mitigation efforts. Past meteorological droughts are identified and analyzed using rainfall frequency analysis, the Bhalme and Mooley Drought Index (BMDI), a drought area index (DAI); and a new method of identifying and rating individual droughts on the basis of BMDI and DAI. According to this analysis, the most severe statewide drought event began in September 1977 and lasted 6 months. No statewide drought event exceeded 6 months. The overall recurrence interval for statewide drought is about 3.3 years. All but three of 27 statewide droughts since 1895 took place during four distinct periods: 1897–1906, 1919–1933, 1941–1953, and 1971–1986. Statewide droughts are most likely to begin in January, February, August, or November, and most likely to end in February, March, April, May, or October. The most drought-prone regions in the state are near, or leeward, of topographic peaks. Persistence in rainfall is not seen for annual values but is evident in monthly totals. Many droughts, but not all, in Hawai‘i are associated with El Niño. Most El Niño events are associated with drier than normal winters in Hawai‘i. If global climate change resulted in a 2 degree increase in air temperature for the state, water supply would be negatively affected because of higher evaporation, even if rainfall increased by 10%.

Well levels in many areas of Hawai‘i are observed to decline during drought. In thick systems, such as the Pearl Harbor aquifer, reduced recharge during droughts may cause decreases in the thickness of the freshwater lens, but such decreases are too small to have an effect on chloride concentration. Increased pumpage is the predominant cause of increased chloride concentration. Variations in rainfall must be considered primarily due to their influence on demand for water during dry periods.

To illustrate the effect of price adjustments on projected water demand, transfer function models of water demand for O‘ahu water districts. Simulations are based on rainfall, lagged rainfall, price, and a dummy variable representing drought restrictions. As expected, water demand is found to be negatively related to rainfall, lagged rainfall, and, in most districts, price.

Water-management decisions under drought more commonly respond to the hydrological, agricultural, and socioeconomic effects of meteorologic/climatic dryness than to the dryness directly. For this reason, three multiple-criteria decision-making models (MCDM) are developed to illustrate how information primarily on climatic drought can be related to these effects and how in turn such effects can be linked to water-management decisions. One used multiobjective optimization to design land-use patterns that respond to concerns about urbanization while

addressing goals regarding groundwater recharge and water demand during drought. The other two use optimization together with multicriteria prioritization (the Analytic Hierarchy Process) to address the problems of water allocation and of project selection for water-supply-system expansion.

KEYWORDS: drought, rain gages, groundwater, parametric hydrology, water demand, water supply, resource allocation, pricing, time-series analysis, forecasting; Bhalme-Mooley drought index, Palmer drought severity index, Hawaii State

EXECUTIVE SUMMARY

Drought is a chronic and troublesome problem in Hawai'i, at one time or another affecting virtually every part of the state. These events often reduce crop yields; kill livestock; desiccate streams, irrigation ditches and reservoirs; deplete groundwater supplies; and lead to forest and brush fires. Periods of drought invariably give rise to water crises, sometimes requiring imposition of emergency conservation measures. Growth of resident and visitor populations and associated land development, along with increases in per capita water consumption, can be expected to increase the frequency and severity of impacts of prolonged dry spells.

This report describes an investigation of the spatial distribution, frequency, duration, intensity, and impacts of historical droughts in Hawai'i and demonstrates the utility of this information for short- and long-term drought mitigation efforts. The research consists of analysis of rainfall data to estimate probabilities of dry periods, to identify past drought events, and to determine the characteristics of drought; compilation of descriptive reports of droughts and their impacts; comparison of objective and descriptive drought data; examination of environmental impacts associated with drought occurrence; evaluation of water demand and its relationship to rainfall deficit; analysis of changes in groundwater level and quality associated with drought; and demonstrations of the use of drought information in short- and long-term decision making.

Meteorological Drought Characteristics

Much of the work in this project was devoted to the identification and analysis of past meteorological droughts using the following methods: rainfall frequency analysis; the Bhalme and Mooley drought index (BMDI), a drought area index (DAI); and a new method of identifying and rating individual droughts on the basis of BMDI and DAI. These indicies are used to investigate persistence of annual and monthly rainfall, conditional drought probabilities, relationship between drought occurrence and El Niño, and the potential influence of climate change on drought occurrence in Hawai'i.

For assessing drought frequency and identifying specific drought events on the basis of rainfall, a network of representative long-term raingage stations was selected on each island. The observed frequencies of low rainfall for 3-, 6-, 9-, and 12-mo durations were found to be well described by the normal distribution. From the fitted distribution, rainfall totals were determined for return periods of 2-, 3-, 5-, 10-, 20-, 30-, 50-, 100-, and 200-yr and plotted on island maps for spatial analysis. In all, 36 maps were produced for each island, providing a comprehensive picture of the spatial distribution of drought in Hawai'i which can be interpreted for a wide range of applications.

To identify specific drought occurrences, as evinced by the rainfall record, and to examine the duration, intensity, and spatial extent of the events, the BMDI was applied to the monthly rainfall series at each of the selected network raingage stations. Graphs were developed that depict the monthly BMDI time series for each island. Graphs were also developed for each of the 48 stations in the network and for the state as a whole. The annual averages were also examined. The DAI of each island and the state as a whole was computed from the monthly BMDI time series. DAI is the percentage of stations in any given month with a BMDI below a selected threshold.

A new method of identifying and rating individual droughts on the basis of the BMDI and DAI indices was developed and applied to each island. The most severe droughts, during the period of record on each island, were identified and ranked. Droughts were identified for individual stations, each island, and the state as a whole. In each case, the distribution of drought severity was examined by plotting the computed severity for each station during the drought period on maps. These maps allow us to identify any recurrent spatial patterns of drought. The drought event lists also enabled us to look for months in which droughts are most likely to begin or end, and to observe the range of drought duration.

The results of the meteorological analysis include the following. The most severe statewide drought event began in September 1977 and lasted 6 months. No statewide drought event exceeded 6 months. The overall recurrence interval for statewide drought is about 3.3 yr. All but 3 of 27 statewide droughts since 1895 took place during four distinct periods: 1897–1906; 1919–1933; 1941–1953; and 1971–1986. Statewide droughts are most likely to begin in January, February, August, or November, and most likely to end in February, March, April, May, or October. The most drought-prone regions in the state are near, or leeward of topographic peaks. Persistence in rainfall is not seen for annual values, but is evident in monthly totals. Many, but not all, droughts in Hawai'i are associated with El Niño. Most El Niño events are associated with drier than normal winters in Hawai'i. If global climate change resulted in a 2°C increase in air temperature for the state, water supply would be negatively affected because of higher evaporation, even if rainfall increased by 10%.

Descriptive Accounts of Occurrence and Impacts of Drought

Based on newspaper accounts, plantation records, and other relevant published and unpublished sources, all available references to drought occurrence in Hawai'i since the year 1860 have been complied and used to identify droughts and rate their severity. These accounts of past droughts offer an independent method of assessing drought occurrence and characteristics. We used this descriptive database to see how valuable historical descriptive accounts are in identifying the frequency and characteristics of drought in a region and to associate actual impacts with droughts of different severity as determined by objective criteria (rainfall-based indices).

Environmental Impacts of Drought

Drought impacts many elements of the environment. This report covers impacts on air temperature, streamflow, soil moisture, and groundwater. By computing temperature anomalies during droughts, we were able to show that most, but not all, events are associated with higher than normal temperatures. Streamflow and soil moisture were shown to closely follow the drought index time series.

In many parts of the state, groundwater is the primary source of water for municipal and agricultural uses. In these areas, well levels are observed to decline during drought. Analysis was done for two aquifers, one thick (Pearl Harbor) and the other thin (Kona), by examining time series of rainfall, recharge, pumpage, water levels, and chlorides. In the Pearl Harbor aquifer, reduced recharge during droughts may cause a decrease in freshwater lens thickness, but such decreases are too small to have an effect on chloride concentration. Increased pumpage is shown to be the predominant cause of increased chloride concentration. Variations in rainfall must be considered primarily due to their influence on demand for water during dry periods. In the Kona aquifer, on the other hand, the transition zone between fresh and salt water is much nearer the pump intakes, and small changes in lens thickness associated with reduced recharge during droughts may bring salt water within the radius of influence of the pump. As with a thick aquifer, however, pumping rate and well depth are probably the predominant factors affecting the quality of the water.

Drought Management

Economic theory suggests that urban water systems could adapt to drought without imposing use restrictions simply by raising water rates. The analysis presented here adds to evidence of the viability of the pricing strategy. Data for the island of O‘ahu is used to estimate transfer function models of water demand for each water district. Models include rainfall, lagged rainfall, price and a dummy variable designating periods of drought restrictions, in addition to ARIMA error structures. As expected, water demand is negatively related to rainfall and lagged rainfall. In most districts, the price coefficient is also negative. The use-restrictions dummies generally seem to have no significant effect. Simulations demonstrate the effect of price adjustments on projected water demand.

The usefulness of any of the information produced by the various analyses in this project depends upon the extent to which water managers and others concerned with drought management can access this information. We have selected several management situations and demonstrated the use of multiple-attribute decision-making (MADM) models in these situations to utilize the newly derived drought information. Three case studies were developed. The first is situated on Maui, where the interregional allocation of water under various drought scenarios was examined. The second case, also on Maui, looks at water development project selection as a long-term strategy to improve management options under drought conditions. The third case, in the Pearl Harbor basin on O'ahu, focuses on the effects on future drought impacts of land-use change decisions.

The first case study treats the question of how to determine allocation under drought and of the role statistical information on meteorological drought can play in such a determination. First, the concept of allocation is discussed, four of its principal elements are identified, and the potential of different kinds of drought to effect changes in an existing allocation is highlighted. Next, key facets of the county water-management decision environment are identified, followed by the description of a model that utilizes information on patterns of past drought to help determine how existing water allocation should change in the face of current or anticipated drought. A hypothetical case study patterned after the situation on Maui illustrates the procedure.

The procedure uses information from three sources: a drought database and statistical analysis covering a 30-yr period; a model based on the analytic hierarchy process (AHP) which helps integrate this information with water managers' judgments to estimate future drought likelihood and evaluate impacts accordingly; and a multiobjective optimization model that determines the best allocation of water in view of the predicted impacts.

Projects to improve water-supply systems may be designed to satisfy various objectives, and the second case study presents a way to incorporate such multiple, conflicting objectives in the selection of water-supply projects. Since drought may affect the relative importance of each objective, drought characteristics play an important role in the procedure.

The approach begins by defining drought scenarios and the probabilities of their occurrence. It then identifies criteria (objectives) with reference to which proposed projects should be judged. The scenarios, criteria, and projects are then arranged into a hierarchy, and the AHP is employed to evaluate the relative attractiveness of each project with respect to each relevant criterion under all scenarios. The outcome of the process is a set of weights which serve to measure the overall attractiveness of each project. The weights are then used in the objective function of an integer program, the solution of which identifies the optimal set of projects subject to constraints on budget and project interdependence. The procedure is illustrated in a quasi-hypothetical case study tailored after Maui's Upcountry Water System Improvements Master Plan. The procedure is flexible and relatively easy to learn and use, but it presumes some experience in formulating optimization models.

A recent decision to allow higher levels of urban development in Central O'ahu, Hawai'i, has heightened the concern about possible loss of agricultural land and further drops in groundwater levels. The third case study examines such potential impacts and offers a procedure for incorporating knowledge of impacts into land-use planning. A water-balance simulation model was used to compute the change in groundwater recharge under changes in land use and irrigation technology. The resulting changes, together with estimated water demands for the agricultural, commercial, and residential sectors, are then included in a multiobjective programming model that identifies optimal patterns of land-use conversion under different objective tradeoffs. Objectives examined are the minimization of agricultural land loss and of water demand, and the maximization of recharge over withdrawal. The second objective pertains to water management during drought, while the third refers to sustainable groundwater management. Results show that, depending on the importance given these two objectives, land moving out of sugarcane will differ significantly in amount and by type of irrigation presently used. Their relative importance thus needs to be determined if water is to play a coherent and guiding role in land-use planning.

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GLOSSARY

AGCONV	Land Conversion Out of Agriculture
AHP	Analytic Hierarchy Process
AR	Autoregressive Term
ARIMA	Autoregressive Integrated Moving Average
BMDI	Bhalme and Mooley Drought Index
COMLAND	New Commercial/Industrial Land
CPI	Consumer Price Index
DAI	Drought Area Index
DBCP	1,2-Dibromo-3-Chloropropane
DEPY	Drought Events Per Year
DMPM	Drought Months Per Month
DUM	Dummy Variable
DW	Durbin-Watson
ENSO	El Niño/Southern Oscillation
GCM	General Circulation Models
LANDRL	New Low-Density Residential Land
LANDRM	New Medium-Density Residential Land
MA	Month-lagged Autoregressive Term
MCMR	Minimum Consecutive-Month Rainfall
NETDEM	Net Demand
NETGW	Net Groundwater
PDSI	Palmer Drought Severity Index
PHGWCA	Pearl Harbor Groundwater Control Area
QBO	Quasi-Biennial Oscillation
RAI	Rainfall Anomaly Index
RP	Return Period
SAR	Seasonal Autoregressive Term
SKN	State Key Number
SOI	Southern Oscillation Index
SST	Sea Surface Temperature
WRRC	Water Resources Research Center
WW	Raw Pumpage in Windward District
WWF	Pumpage forecast based on the Windward Equation Using Observed Values of Price and Rainfall
WWFP	Pumpage forecast with 25% price increase
WWFR	Pumpage forecast with 50% lower rainfall

CONTENTS

Figures

Tables

INTRODUCTION

Drought is a chronic and troublesome problem in Hawai‘i (Fig. 1). At one time or another, virtually every part of the state has been seriously affected by drought. These events often reduce crop yields, kill livestock, desiccate streams and irrigation ditches and reservoirs, deplete groundwater supplies, and lead to forest and brush fires. Periods of drought invariably give rise to water crises that sometimes require imposing of emergency conservation measures. Growth of resident and visitor populations and associated land development, along with increases in per-capita water consumption, can be expected to increase the frequency and severity of impacts of prolonged dry spells.

Governmental efforts to mitigate drought impacts can be grouped into short- and long-term strategies. During a drought event, water managers need to know when to take action and decide how best to conserve the dwindling supply while providing water for the most critical needs. They may have to alter the allocation scheme that would apply under normal conditions. Since drought is part of climate's natural variability, planning for future dry periods is prudent. The inevitability of drought must be taken into account in assessing availability of water for future land and water development. Both short- and long-term decisions require knowledge of drought duration, severity, and spatial extent. Meteorological prediction of drought is not yet achievable. However, by studying past events, we can assist in crisis response and long-term drought planning.

The purpose of this study is to investigate the spatial distribution, frequency, duration, intensity, and impacts of historical droughts in Hawai‘i and to demonstrate the utility of this information for short- and long-term drought mitigation efforts. The research presented here consists of analysis of rainfall data to estimate probabilities of dry periods, to identify past drought events, and to determine the characteristics of drought; compilation of descriptive reports of droughts and their impacts; comparison of objective and descriptive drought data; examination of environmental impacts associated with drought occurrence; evaluation of water demand and its relationship to rainfall deficit; analysis of changes in groundwater level and quality associated with drought; and demonstrations of the use of drought information in short- and long-term decision-making.

Drought Impacts in Hawai‘i

Justification for a comprehensive study of drought characteristics in Hawai‘i comes from the long experience of the state's residents, plantation operators, ranchers, and water officials with the costly impacts of numerous previous drought events. That such drought impacts have

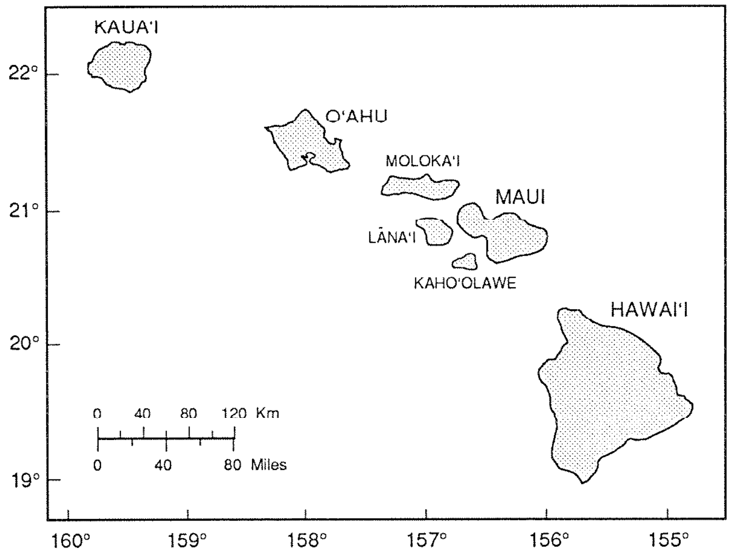


Figure 1. Location map, Hawai'i State

occurred can be verified by examining descriptive accounts of drought from newspapers, government reports, and other sources. In Table 1, we have summarized a compilation of descriptive drought accounts. This summary represents groupings from a total of 297 individual reports. The table gives the beginning and ending dates of apparent drought events based on single or multiple references to drought impacts on one or more island. Where no ending date is given, corresponding report(s) were for only a single month. All islands mentioned in the references and reported water supply (W), crop (C), livestock (L), and fire (F) impacts are indicated. It is clear that drought recurs regularly and that no island is immune to its negative impacts. More detailed analysis of this descriptive drought database and comparison with objective drought indices will be presented (see pp. 85–94).

Previous Drought Studies in Hawai'i

There have been several previous studies of specific drought events and of the occurrence of drought in certain regions of the state. They include the report by Yeh, Carson, and Marciano (1950) who briefly discussed drought cases on O'ahu from 1933 to 1940. Blumenstock and Price (1967) include a general discussion of drought in their treatise on the climate of Hawai'i. Vogl's (1969) paper on Hawaiian vegetation ecology makes reference to drought-induced fires. Rho (1974) and Fok and Miyasato (1975, 1976) reported on the extensive drought damage that occurred in central Maui as a result of the severe summer drought of 1973. Bowles and Mink (1975) studied stochastic output of surface water of the agricultural region of Pololu Valley,

TABLE 1. DESCRIPTIVE ACCOUNTS OF DROUGHT EVENTS IN HAWAI'I, 1860–1986

DROUGHT PERIOD From	To	ISLANDS AFFECTED*						IMPACT†			
1860 Oct						Oa					
1861 Nov						Oa		W			
1866 Sep			Ma			Oa	Ka				
1869 Feb	1869 Mar	Ha				Oa		W	C		
1872 Aug	1872 Sep		Ma			Oa		W	C	L	
1873 Feb		Ha						W			
1873 June	1873 Nov	Ha	Ma			Oa			C	L	
1875 Sep	1876 Feb		Ma								
1876 May		Ha						W	C		
1876 July	1876 Oct		Ma			Oa		W		L	
1877 Nov	1878 Apr	Ha	Ma			Oa		W	C	L	
1881 June		Ha									
1881 Oct	1881 Nov	Ha	Ma				Ka	W	C		
1882 Mar		Ha						W			
1882 May		Ha						W			
1882 Nov		Ha									
1883 Nov		Ha		Mo						L	
1884 Mar		Ha						W			
1886 July	1886 Aug	Ha	Ma	Mo	La	Oa	Ka			L	
1887 June		Ha									
1889 Jan	1889 July	Ha	Ma			Oa	Ka		C	L	
1891 Aug		Ha								L	
1892 Apr		Ha						W			
1892 June		Ha									
1892 Aug	1892 Sep		Ma				Ka		C		
1893 Aug	1893 Oct	Ha	Ma				Ka	W	C	L	
1894 May	1894 Nov	Ha					Ka		C		
1895 Apr		Ha									
1897 Apr	1897 Aug	Ha	Ma			Oa		W	C		
1898 Apr			Ma						C		
1899 Feb		Ha						W	C		
1901 June	1901 Sep	Ha	Ma					W	C		F
1902 July	1902 Oct	Ha									F
1905 Jan	1905 Apr	Ha	Ma			Oa		W	C	L	F
1906 Feb		Ha	Ma		La		Ka				

DROUGHT PERIOD From	To	ISLANDS AFFECTED*						IMPACT†			
1907 May		Ha						W			
1908 Feb			Ma					W			
1908 May		Ha	Ma								
1908 Dec	1909 Mar	Ha	Ma				Ka	W		L	
1909 June	1909 Oct	Ha	Ma			Oa					
1910 Sep		Ha	Ma								
1911 Aug			Ma								
1912 July		Ha									
1913 Sep		Ha	Ma	Mo	La	Oa	Ka				
1914 Feb						Oa					
1915 Mar		Ha									
1916 Aug	1916 Sep					Oa					
1917 Apr	1917 Oct	Ha	Ma	Mo		Oa		W	C	L	
1918 Sep	1920 Oct	Ha	Ma	Mo	La	Oa	Ka	W	C	L	F
1921 June		Ha	Ma					W		L	
1921 Aug	1921 Nov		Ma	Mo	La	Oa	Ka		C	L	
1922 June	1922 Aug	Ha	Ma	Mo	La	Oa	Ka	W	C	L	
1923 Mar						Oa					
1923 June		Ha	Ma	Mo	La	Oa	Ka		C		
1924 Jan	1924 Feb	Ha	Ma	Mo	La	Oa	Ka	W	C	L	
1924 June	1924 July	Ha	Ma	Mo	La	Oa	Ka	W	C		
1925 Jan		Ha	Ma	Mo	La	Oa	Ka	W			
1925 Dec	1926 May	Ha	Ma	Mo	La	Oa	Ka	W	C	L	
1927 Feb		Ha						W	C		
1928 Mar		Ha	Ma	Mo	La	Oa		W			
1928 June		Ha						W			
1929 July											
1931 Jan	1931 Mar	Ha	Ma	Mo	La	Oa	Ka	W	C		
1931 June		Ha	Ma	Mo	La	Oa	Ka	W			
1932 Sep	1932 Oct	Ha							C	L	
1934 Nov			Ma						C		
1940 Jan	1940 Feb	Ha						W			
1941 Feb						Oa		W	C		
1941 May	1941 June	Ha				Oa		W	C		
1944 Apr		Ha	Ma	Mo	La	Oa	Ka		C	L	

TABLE 1.—*Continued*

DROUGHT PERIOD From	DROUGHT PERIOD To	ISLANDS AFFECTED*	IMPACT†
1944 June		Oa	W
1945 Apr		Ma Mo	C L
1945 Aug		Ha Ma Mo La Oa Ka	C
1949 Apr		Ma	C
1950 June		Ha Ma Mo La Oa Ka	L
1950 Dec	1951 Jan	Ha	W
1951 Dec	1953 Oct	Ha Ma Mo La Oa Ka	W C L
1954 Jan	1954 Jan	Ha	C L
1954 Apr	1954 May	Ha Mo	C L
1954 Nov			F
1957 Jan	1957 Mar	Ma	
1957 June		Ma	C L
1957 Oct		Ma	W
1958 Jan	1958 Feb	Ha	W C
1958 July	1958 Sep	Ha	L
1961 Apr	1961 Oct	Ha	C L
1962 Apr	1963 Dec	Ha Ma Mo La Oa Ka	W C L
1964 July		Ha	L
1965 Apr		Ha	W C
1965 June	1965 Oct	Ha	W C
1966 May	1966 June	Ha Ma Mo La Oa Ka	W C L
1966 Oct		Ha	C L
1967 Oct	1967 Nov	Ha	W C
1968 Oct	1968 Nov	Ha	W
1969 June	1969 June	Ha Ma	W
1969 Oct		Ha Ma Mo La Oa Ka	W L F
1970 Feb	1970 Apr	Ha Oa	W C L F
1971 June	1971 Sep	Ha Ma Mo La Oa Ka	W C L
1971 Dec	1972 Mar	Ha Ma Mo	W C L F
1972 June	1972 June	Ha Ma	C L
1972 Nov	1973 Nov	Ha Ma Mo La Oa Ka	W C L F
1974 Feb	1974 Oct	Ha	W C L
1975 Apr	1975 May	Ka	
1975 Aug	1975 Nov	Ha Ma Mo La Oa Ka	W C L
1976 Dec	1977 Mar	Ha Ma Oa	W C L
1978 Jan	1978 Apr	Ha Ma	C L
1980 Jan	1980 Feb	Ha	
1980 Oct	1981 Aug	Ha Ma Oa	W C L F
1983 Feb	1983 Mar	Ha Ma	W C L F
1983 Nov	1983 Dec	Ha Ma Oa	L F
1984 Mar	1984 Oct	Ha Ma Mo La Oa Ka	W C L F
1986 Feb	1986 Mar	Ha Ma Oa Ka	W C L

NOTE: Represents groupings from 297 individual reports.
*Ha = Hawai'i, Ma = Maui, Mo = Moloka'i, La = Lāna'i, Oa = O'ahu, Ka = Kaua'i.
†W = water supply, C = crop, L = livestock, F = fire.

Hawai'i Island. Hawai'i was included in a report by Matthai (1979) on the 1976-1977 drought in North America. The 1980-1981 drought affecting parts of the islands of Hawai'i and Maui was investigated by Haraguchi (1981) and Haraguchi and Giambelluca (1982). Matsunaga (1983) investigated statistical aspects of dry spells on the island of Hawai'i. Investigations by several authors (Meisner 1976; Wright 1979; Horel and Wallace 1981; Lyons 1982; Haraguchi and Matsunaga 1985; and Chu 1989) have focussed on the relationship between negative rainfall anomalies in Hawai'i, the El Niño/Southern Oscillation (ENSO) (the recurrent warming of eastern equatorial Pacific surface waters), and related atmospheric and oceanic changes throughout the equatorial Pacific.

Extensive literature and large databases exist on drought-related topics in Hawai'i, including precipitation, streamflow, groundwater recharge, agricultural yields, irrigation, municipal water demand, and water conservation (see bibliographies by Pfund and Stellar 1971; and Fujimura and Murabayashi 1983). Rainfall observations in Hawai'i date from the 1840s. Over the years numerous maps of rainfall in Hawai'i have been prepared. Taliaferro (1959) prepared monthly and annual median rainfall maps for all major islands, based on a common 25 yr base period ending in 1957. Meisner, Ramage, and Schroeder (Division of Water and Land Development 1982) updated and revised Taliaferro's annual maps. A comprehensive set of median and mean, monthly and annual rainfall maps was done by Giambelluca, Nullet, and Schroeder (1986).

Defining Drought

Much has been written on defining and analyzing drought. Wilhite and Glantz (1987) review the problem of drought definition (see also Dracup, Lee, and Paulson 1980*a*,*b*; Dracup and Lee 1981; Gregory 1986; Jackson, 1981; Steila 1981; and Yevjevich 1967). Wilhite and Glantz recognize conceptual and operation definitions. Conceptual definitions are general statements that "identify the boundaries of the concept of drought" (Wilhite and Glantz 1987). A good example of a conceptual definition of drought is the statement by climatologist F. Kenneth Hare (1987), "Climatic drought is, among other things, the failure of expected precipitation, over a period long enough for it to hurt." Because they lack specificity, conceptual definitions are not useful for drought assessment.

To analyze drought, an operational definition, usually quantitative, is necessary. An operational definition should be objective, though this usually imposes a degree of arbitrariness. Drought can be operationally defined in relative or absolute terms. Relative drought is determined by fluctuations about local mean values, while absolute drought, or aridity, is defined relative to a single reference level. The underlying premise here is that natural and social systems evolve in adjustment with average moisture conditions. Because drought severity depends on the impact of dryness on natural and social systems, it, therefore, varies according to the vulnerability of those systems at the time of the dry spell (Wilhite and Glantz 1987) and according to the system of primary interest to the observer. As a result of these difficulties, no universally acceptable definition of drought is likely to be developed. Drought definition must differ spatially and temporally to account for variations in expected conditions and the vulnerability of nature and society.

According to Dracup, Lee, and Paulson (1980*b*) "drought is generally defined as a water shortage with reference to a specified need for water in a conceptual supply and demand relationship." They identify four decisions an analyst must consider to arrive at an operational drought definition: (1) the water deficit of interest (rainfall, streamflow, or soil moisture); (2) the averaging period of interest; (3) the threshold level to distinguish droughts; and (4) the method of dealing with the regional aspects of drought. The decisions on these issues usually depend on the point of view of the analyst and the intent of the study.

Wilhite and Glantz (1987) group drought definitions into four types: meteorological, hydrologic, agricultural, and socioeconomic. Most drought-evaluation techniques use a meteorological definition of drought. The Palmer drought severity index (PDSI) (Palmer 1965), perhaps the best known meteorological drought evaluation method, is still commonly used (Alley 1984, 1985). The Palmer method produces an index based on precipitation relative to the evapotranspiration requirement. The PDSI gives the moisture state in comparison with the climatic normal for the location and season. Bhalme and Mooley (1980) developed a normalized rainfall approach to drought analysis which has been used extensively (e.g., Mooley and Parthasarathy 1983; Chu 1983; and Olapido 1985). The Bhalme and Mooley drought index (BMDI) is scaled to resemble the Palmer index. The rainfall anomaly index (RAI) was developed by Rooy (1965). Olapido (1985) compared the PDSI, BMDI, and RAI using data from the Great Plains of North America. In comparing the first two indices, he noted good agreement, but cited the following advantages of the BMDI over the PDSI: (1) does not require estimation of evapotranspiration or soil water capacity, (2) is simpler to program and adapt to difficult climatic regions, (3) uses standard deviation and coefficient of variation to account for significant seasonal precipitation, (4) assesses drought relative to each station's extreme values, and (5) provides a better measure of the effects of short periods of dry weather.

Because of dependence on water supply for domestic consumption, industrial activity, and irrigated agriculture, drought is often most meaningfully defined in terms of the levels of streams, lakes, reservoirs, and groundwater. While hydrological and meteorological droughts are certainly related, they do not always occur in phase (Wilhite and Glantz 1987). Hudson and Roberts (1955) suggested a method of analyzing consecutive low flow months to evaluate drought with reference to reservoir storage. Burnash and Ferral (1973) proposed the use of generalized hydrological modeling as a drought evaluation method. Dezman *et al.* (1982) developed the Surface Water Supply Index for use in high-elevation basins in Colorado. Sen (1980) used mean annual streamflow to define multiyear drought. Zelenhasic and Salvai (1987) used a related procedure to analyze streamflow droughts of duration less than a year. Alley (1985) suggested the use of the PDSI to assess hydrologic drought.

Agricultural indices of drought generally focus on the storage of water within the soil root-zone reservoir or the relative rate of water use by plants. Nullet and Giambelluca (1988) and Giambelluca, Nullet, and Nullet (1988) used the ratio of actual to potential evapotranspiration to define agricultural drought on Pacific islands. Numerous other agricultural drought definitions have been developed (see Barger and Thom 1949; Havens 1954; Hershfield, Brakensiek, and Comer 1973; and Nieuwolt 1978).

The socioeconomic definition of drought recognizes that drought is influenced by anthropogenic variations in demand as well as by natural variations in supply. Under this framework, drought occurrence in a region may become more or less frequent, severe, or widespread through time as a result of changes in population, shifts in economic activities, or advances in technology related to water supply.

According to Dracup, Lee, and Paulson (1980*a*), drought can be described in terms of three attributes: duration (D), severity (S), and magnitude (M), related as

$$M = \frac{S}{D}$$

where M is average water deficit during drought, S is cumulative water deficit during drought, and D is number of consecutive time units for which water deficit exists. Any two of these parameters completely specifies a drought.

Causes and Prediction of Drought

Regardless of its precise definition, drought is lower than expected water supply that results from less than expected precipitation or higher than expected evaporation (or both). Changes in natural or social systems can affect the threshold for drought, but triggers for droughts are atmospheric. Since periods of high evaporation demand are likely to coincide with periods of low rainfall, the cause of drought ultimately lies in the atmospheric circulation anomalies or surface conditions that produce deficient rainfall. In general, periods of deficient rainfall are associated with a drier or more stable than normal atmosphere. A range of large-scale atmospheric circulation patterns, ocean or land surface conditions, and extraterrestrial influences have been put forth as possible underlying causes of drought-producing atmospheric conditions.

Anticyclonic circulation is associated with subsiding air, a condition that produces a stable, arid atmosphere. In middle and higher latitudes, a condition known as "blocking" occurs when north-south meanders in upper-level westerly winds become elongated leading to quasi-stationary, closed anticyclonic circulation cells that block migration of precipitation-producing weather systems. The severe 1975 to 1976 drought in southern England (Doornkamp, Gregory, and Burn 1980) has been attributed to blocking. Such persistent blocking episodes have been linked with global-scale circulation anomalies (Ratcliffe 1978).

Evidence of alternating wet and dry spells leads to a search for links with atmospheric oscillations. Rasmusson (1987) identifies three oscillations of interest: the quasi-biennial oscillation (QBO), 30- to 60-day oscillations, and the El Niño/Southern Oscillation (ENSO). The QBO is a 2.25-year cycle whose signal is seen most strongly in equatorial stratospheric winds. Various surface weather features have been correlated with the QBO, but only marginally (Rasmusson 1987). Rainfall fluctuations, as well as the characteristics of the Indian monsoon, have been linked with the 30- to 60-day oscillations first identified by Madden and Julian (1971). El Niño, the anomalous warming of the eastern equatorial Pacific sea surface, and the Southern Oscillation, the seesaw in atmospheric mass between the eastern and western equatorial Pacific, are two parts of a global-scale ocean-atmospheric phenomenon now known as ENSO. Rasmusson (1987) calls ENSO "the most notable and pronounced example of global climate variability on the interannual time scale." It has been strongly associated with positive and negative rainfall fluctuations throughout the tropics, including Hawai'i where it is associated with winter drought (Wright 1979; Horel and Wallace 1981; Lyons 1982; and Chu 1989).

Various researchers have noticed periodicities in the occurrence of drought in some regions. Such long-term cycles have been linked with solar and lunar cycles. Using a DAI for the western U.S., based on tree-ring data, significant relationships with the Hale sunspot cycle (Mitchell, Stockton, and Meko 1979) and the lunar nodal regression (Bell 1981; and Currie 1981) were found. Hameed (1984) detected solar and lunar influences in the record of Nile River floods.

El Niño is but one of many sea surface temperature anomalies suspected of influencing drought occurrence. Namais (1965) has associated the strength and position of pools of relatively warm and cold surface waters in the North Pacific and North Atlantic with persistent climate fluctuations in North America and Europe, respectively.

The apparent persistence of drought has led some to postulate the existence of some kind of feedback between drought-related surface conditions and drought-producing atmospheric characteristics (Rasmusson 1987). According to Landsberg (1982), reduced soil moisture and consequent lower evaporation during drought inhibit development of local convective storms. Similar reasoning associates human-induced land surface change as Amazonian deforestation (Shukla, Nobre, and Sellers 1990) and Sahelian overgrazing (Charney 1975) with long-term increase in regional aridity.

Improved understanding of the underlying causes of drought has given hope for the possibility of reliably predicting drought. Atmospheric scientists are in general agreement that the limit to predictability of instantaneous weather conditions is on the order of a few weeks. However, forecasts with much longer lead-time are possible for time- and space-averaged climatic conditions. Such forecasts would be useful to agricultural and water resource interests for averting some of the impacts of impending or continuing drought. At present, the most promising advances are the continuing development of dynamical models of atmospheric general circulation and the improving understanding of the ENSO phenomenon (Rasmusson 1987). Some improvements may also come from more research on solar and lunar influences on climate and on the influences of 30- to 60-day oscillation. Forecasts will probably remain general, however, as Rasmusson (1987) points out, "major improvements in the spatial resolution of monthly/seasonal precipitation forecasts do not appear likely."

METEOROLOGICAL DROUGHT CHARACTERISTICS

As described in the previous section, droughts may be conveniently divided into four types: meteorological, hydrologic, agricultural, and socioeconomic. While the occurrence and impacts of each type differ because of natural or social vulnerability, all types ultimately result from deficient rainfall. Meteorological drought, the most tractable type to analyze, allows us to independently examine the atmospheric drought signal, and provides the baseline from which other drought types can be studied.

Our analysis of meteorological drought in Hawai'i is made on the basis of rainfall records. After describing the selection of the rain gage network and initial processing of the data, we present the following analyses: the frequency of minimum consecutive-month rainfall for 3- to 12-mo durations; the Bhalme and Mooley Drought Index (BMDI) and Drought Area Index (DAI) for each network station; identification of historical drought events for each station, island, and for the entire state, using BMDI; drought duration, month of onset, and ending month; the spatial patterns of past droughts; determination of the degree of persistence of dry or wet weather; conditional probabilities of continuation of in-progress droughts; concurrence of drought and ENSO events; and possible impacts of global warming on drought occurrence.

Rain Gage Network Selection and Initial Data Processing

The state of Hawai'i has one of the densest rain gage networks in the world. More than 2,000 rain gage sites have operated at one time or another for various lengths of time. The sites tend to be concentrated in areas of cultivation or water supply interest, while other areas of the islands are not as well monitored. The earliest observations of rainfall in Hawai'i date from the 1840s, with some permanent continuous sites beginning in the 1870s. Rainfall data in the form of monthly totals through 1975 was complied and entered into a computer database by Meisner (1978). Data were subsequently updated through 1983 by the Hawaii State Department of Land and Natural Resources (DLNR).

For the purposes of this study, a network of stations was selected from among the larger database. The criteria for selection were (1) longevity—existence of a long-term continuous record; (2) representativeness—location within a recognizable regional rainfall regime; and (3) nonredundancy—location sufficiently distant from other selected stations. Rainfall regions for which representative stations were sought were identified subjectively by using topography, rainfall patterns, and knowledge of dominant regional rain-producing processes (Giambelluca, Nullet, and Schroeder 1986). The resulting network is shown in Figures 2 to 6. Stations are identified by their State Key Number (SKN).

For this project, data for selected network stations were updated through 1986. In addition, based on linear regression of the network station with nearby highly correlated gages, an attempt was made to estimate rainfall for periods when no records were available. Data for the SKN 798 site on O'ahu are taken from two sites approximately 300 m apart. Periods of record are listed for network stations in Table 2.

Minimum Consecutive-Month Rainfall

To summarize meteorological drought information in the most generic manner, without reliance on any particular definition arising from a specific interest group, a conventional rainfall frequency analysis was done. Following a procedure outlined by Hudson and Roberts (1955) for streamflow data, we estimated recurrence intervals for minimum rainfall for durations of 3, 6, 9, and 12 mo. For each duration, rainfall totals were calculated for each overlapping period during the entire record of the gage. These minimum consecutive-month rainfall (MCMR) values were ranked in ascending order, deleting any event overlapping a higher-ranked event. The highest ranked events identify the driest periods at each station for the specified durations.

The method allows us to analyze drought without specification of an arbitrary threshold. Drought is viewed on a severity continuum with an associated recurrence interval scale. Event ranks are transformed into return periods according to

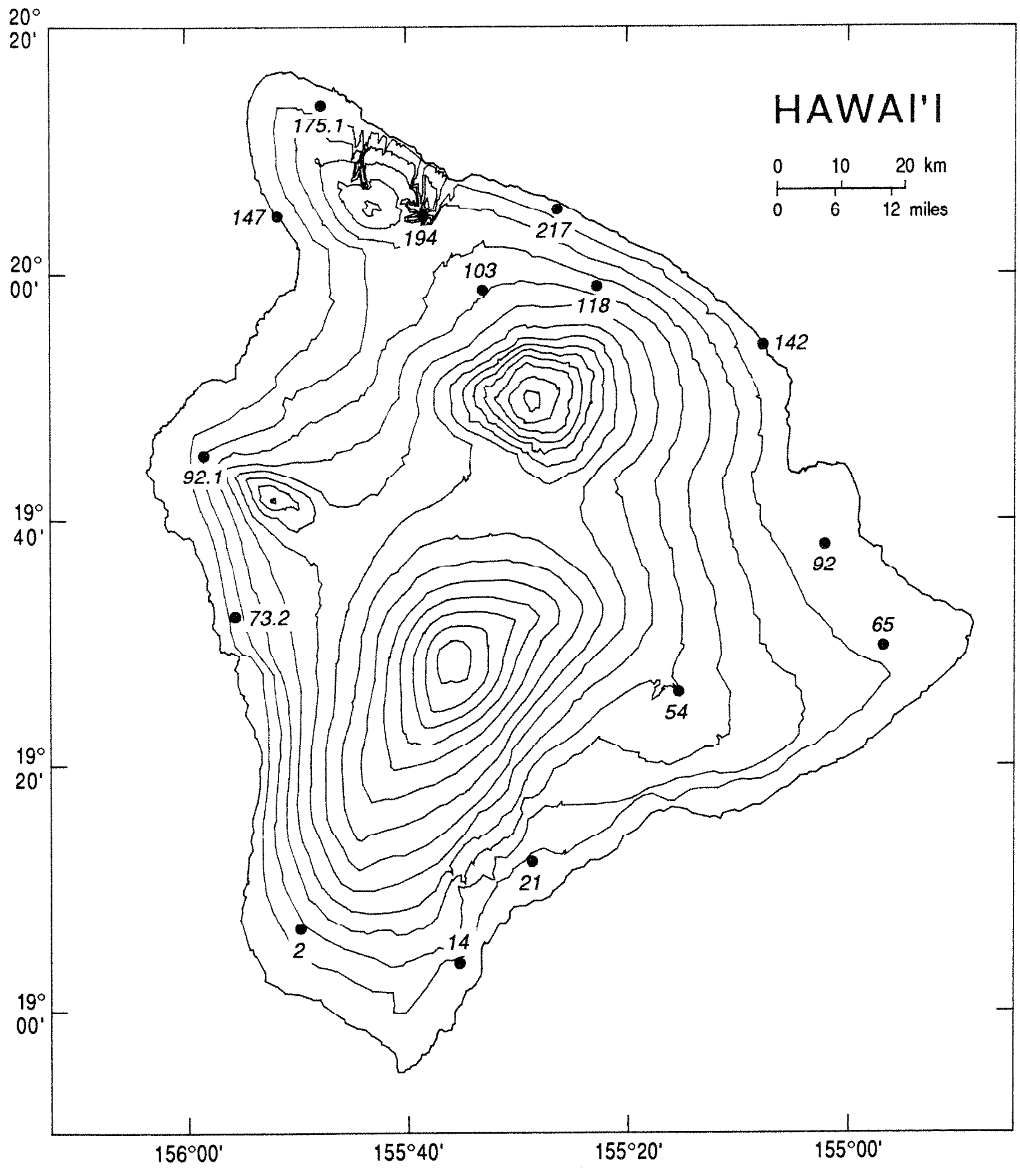


Figure 2. Rain gage network, Hawai'i Island

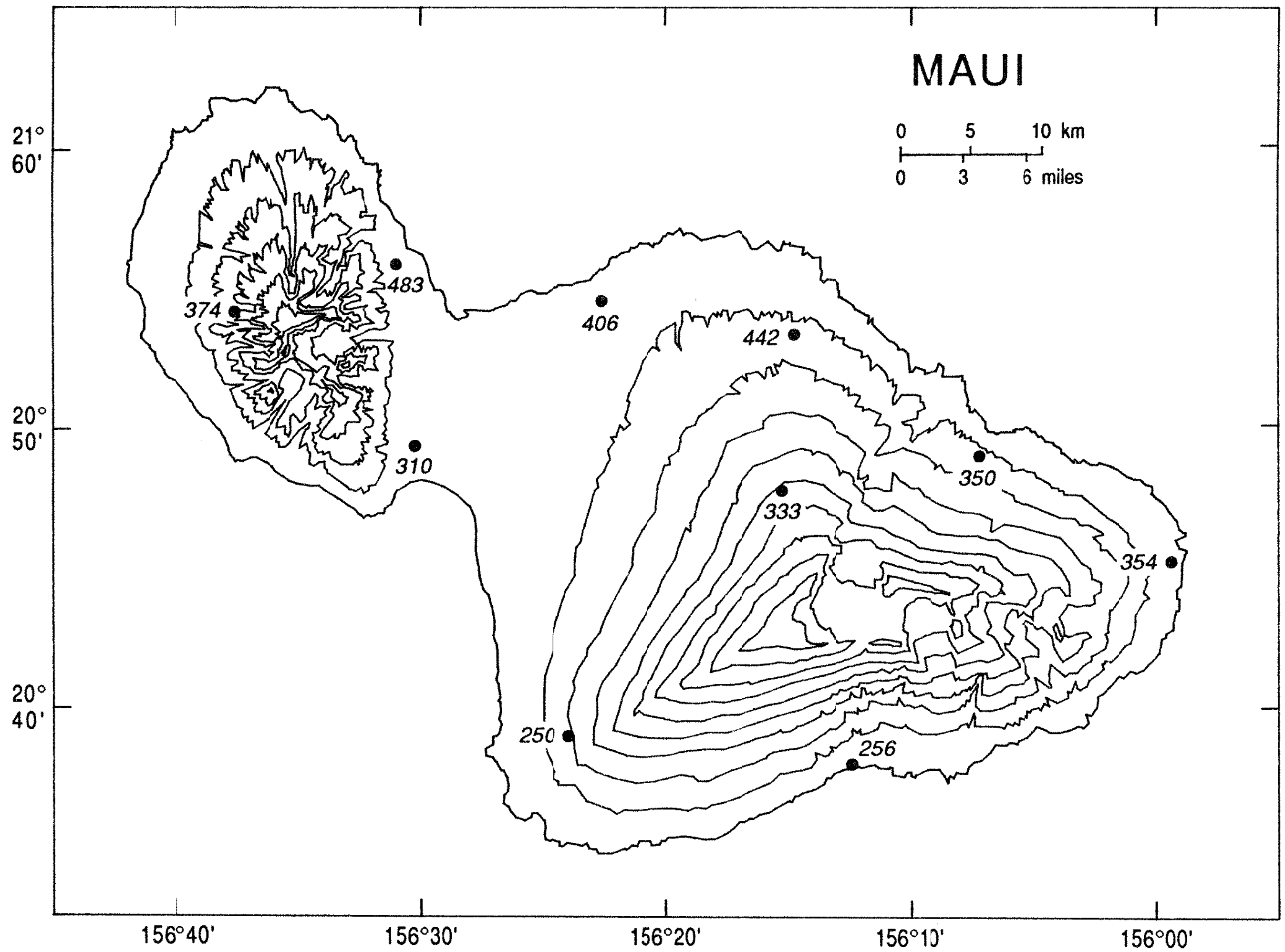


Figure 3. Rain gage network, Maui Island

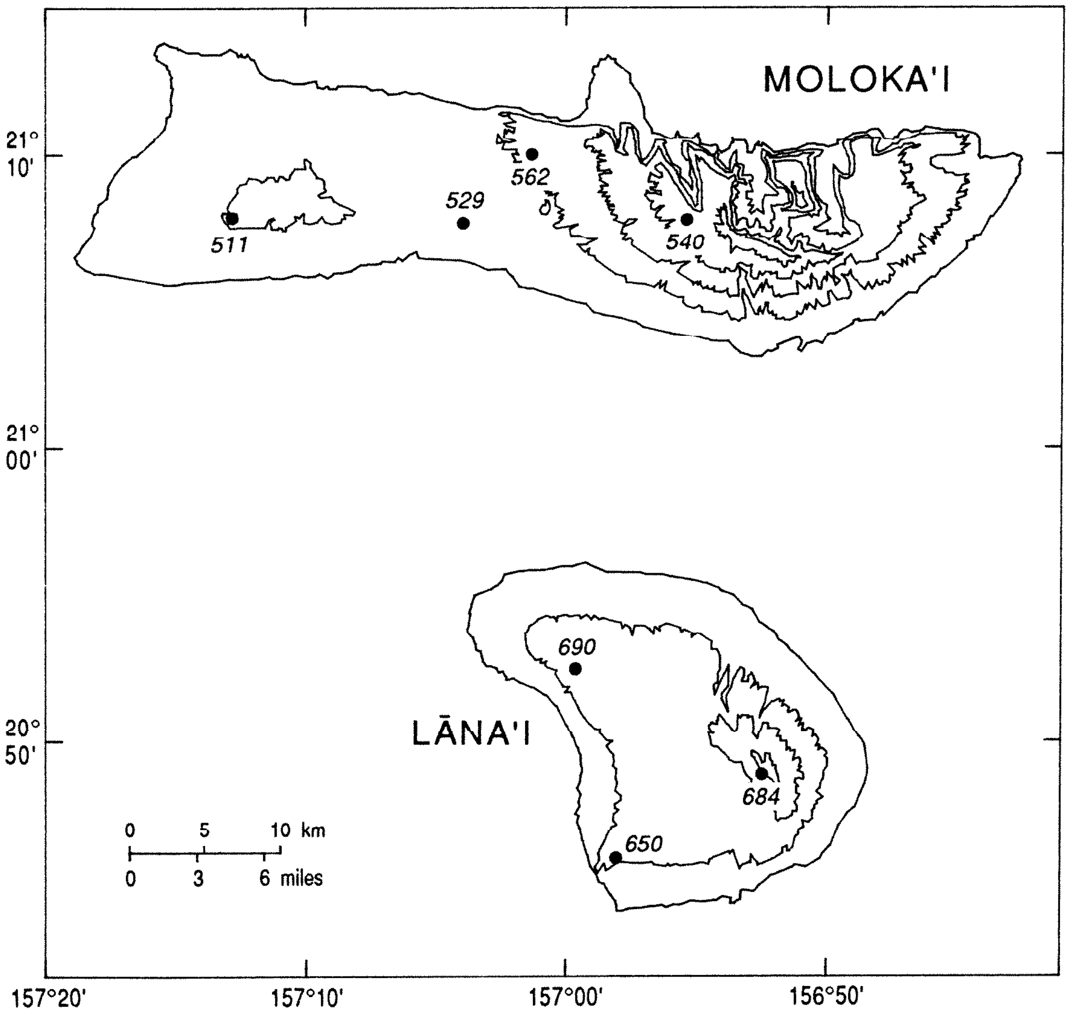


Figure 4. Rain gage network, Moloka'i and Lāna'i Island

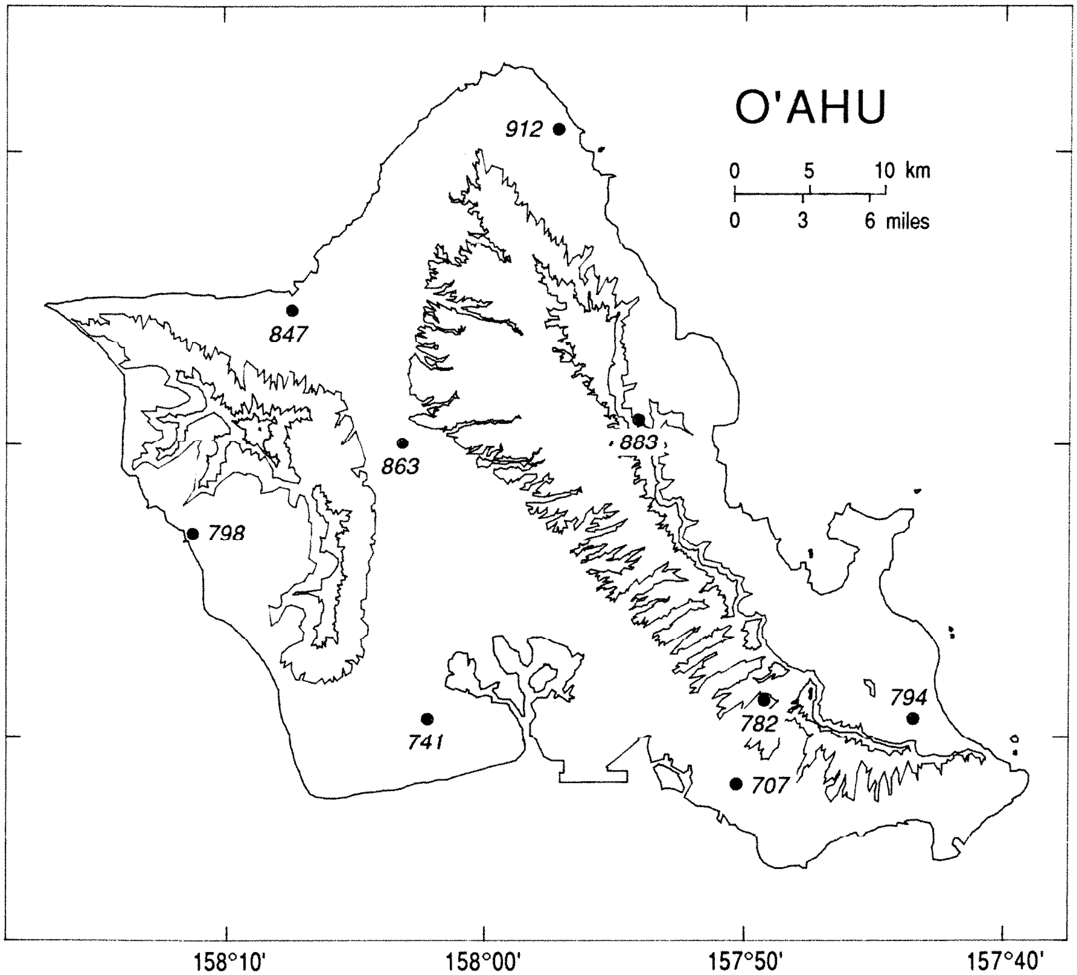


Figure 5. Rain gage network, O'ahu Island

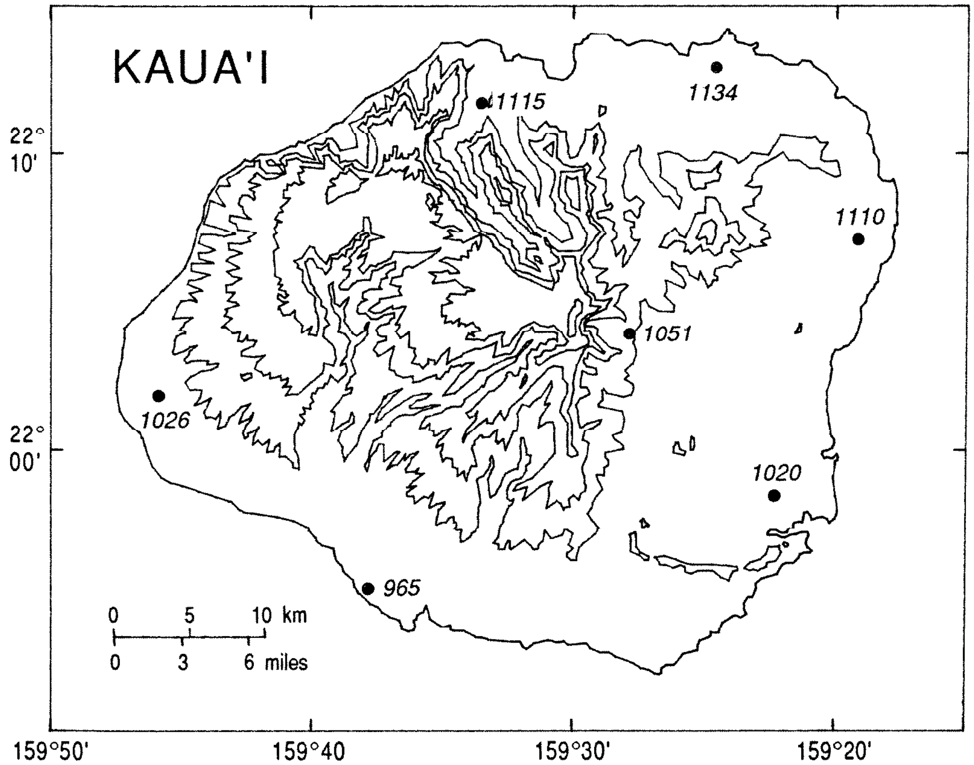


Figure 6. Rain gage network, Kaua'i Island

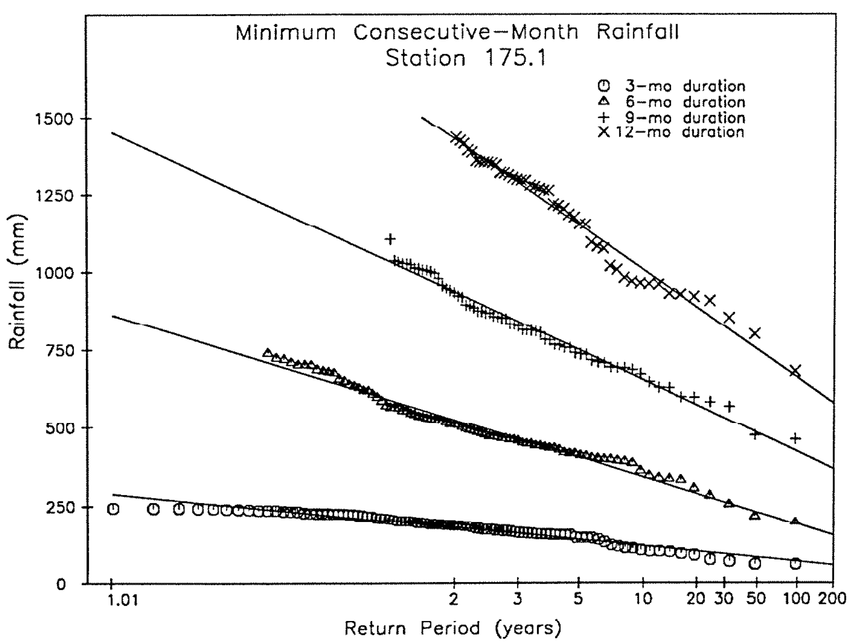


Figure 7. Minimum consecutive-mo rainfall, 3-, 6-, 9-, and 12-mo durations vs. return periods, Sta. 175.1, Hawai'i Island

TABLE 2. STATION NETWORK HEADER INFORMATION

State Key No.	Station Name	Observation Period	Augmented Period*
Hawai'i Island			
2	Manuka	1929–1986	1929–1986
14	Naalehu	1890–1986	1890–1986
21	Pahala	1892–1986	1885–1986
54	Hawaii Nat Pk Hq	1913–1986	1888–1986
65	Pahoa	1902–1986	1891–1986
73.2	Kainaliu	1931–1986	1901–1986
92	Keaauolaa	1901–1986	1880–1986
92.1	Huehue (1960)	1903–1986	1903–1986
103	Makahalau	1910–1986	1909–1986
118	Umikoa	1894–1976	1885–1986
142	Hakalau	1892–1986	1880–1986
147	Beach	1931–1983	1931–1986
175.1	Kohala Mission	1890–1986	1884–1986
194	Alakahi Lower	1910–1986	1902–1986
217	Paauhau-p Sugar	1890–1986	1885–1986
Maui Island			
250	Ulupalakua Ranch	1905–1986	1905–1986
256	Waiopai Ranch 2	1920–1986	1920–1986
310	Reservoir 90	1910–1982	1903–1986
333	Ukulele	1904–1986	1904–1986
350	Paakea	1904–1986	1904–1986
354	Hana	1907–1978	1895–1986
374	Kahoma Intake	1910–1986	1910–1986
406	Paia	1894–1986	1883–1986
442	Lupi Upper	1897–1986	1897–1986
483	Waihee	1898–1986	1883–1986
Moloka'i Island			
511	Maunaloa	1923–1978	1900–1986
529	Field 325	1929–1986	1900–1986
540	Waikolu-m.ranch	1930–1986	1930–1986
562	Kipu	1930–1986	1900–1986
Lāna'i Island			
650	R-8	1914–1986	1892–1986
684	R-4	1924–1986	1924–1986
690	Kanepuu	1914–1986	1892–1986
O'ahu Island			
707	Makiki	1918–1983	1884–1986
741	Ewa Mill	1891–1986	1874–1986
782	Lower Laukaha	1890–1986	1890–1986
794	Mokulama	1894–1986	1874–1986
798	Waianae	1891–1986	1874–1986
847	Waialua	1901–1986	1884–1986
863	Wahiawa Dam	1905–1986	1900–1986
883	Kahana-o Sugar	1916–1986	1916–1986
912	Kahuku	1891–1986	1883–1986
Kaua'i Island			
965	Makaweli	1892–1986	1892–1986
1020	Lihue	1904–1986	1885–1986
1026	Mana	1904–1986	1889–1986
1051	N. Wailua Ditch	1928–1986	1901–1986
1110	Halaula	1902–1986	1885–1986
1115	Pow Hse Wainiha	1908–1986	1908–1986
1134	Kilauea	1885–1986	1885–1986

*Period extended by rainfall estimates from regression analysis.

$$RP = \frac{(n + 1)}{m}$$

where RP is return period (years), n is years of record, and m is rank of event. The return period is the average time, in years, between MCMR totals equal to or less than the given amount. The probability of an MCMR of equal or lower amount in any given year is 1/RP. Fitting (RP, MCMR) points to a cumulative frequency distribution allows interpolation and extrapolation to specific return periods. Normal and log-normal distributions were tested. Based on overall goodness-of-fit, the normal distribution was selected for use. A sample graph of MCMR versus return period for the four durations at Station 175.1 (Kohala Mission, Hawai'i Island) is shown in Figure 7. Using analytical expressions for the best-fit lines shown in the figure, MCMR values for return periods of 2, 3, 5, 10, 20, 30, 50, 100, and 200 years were derived for each station in the network. Sample MCMR values for these return periods are listed in Table 3 for network stations on O'ahu.

By plotting the derived MCMR values for a given return period and duration at appropriate station locations, we were able to construct isohyetal maps depicting the spatial patterns of minimum rainfall. Maps of MCMR for the 5-year return period and 3-, 6-, 9-, and 12-month durations for all islands are shown in Figure 8. Maps for all return periods and durations are given in Appendix Figures D.1–D.5.

The patterns of MCMR give a comprehensive picture of *absolute drought.* The extreme spatial variability in rainfall in Hawai'i is reflected in these patterns. The patterns, in fact, closely resemble those of average rainfall (Giambelluca, Nullet, and Schroeder 1986), and high-intensity rainfall (Giambelluca *et al.* 1984). Areas with relatively high average rainfall also have relatively high minimum and high-intensity rainfall. In many contexts, *relative drought*, based on deviation from average rainfall, is more relevant. However for assessment of the potential for agricultural or water resource development, absolute measures are appropriate. For example, design of reservoir capacity to sustain projected water supply rates would depend on the minimum expected rainfall (in absolute terms). Similarly for estimation of peak irrigation requirements or determination of crop suitability for rain-fed cultivation, minimum absolute rainfall is required.

Bhalme and Mooley Drought Index

To identify specific drought occurrences as evinced by the rainfall record and to examine the duration, timing, and spatial extent of drought events, the BMDI (Bhalme and Mooley 1980) was applied to the monthly rainfall series at each network rain gage station. The BMDI is purposefully similar in appearance to the PDSI (Palmer 1965). Both indicate the relative monthly moisture condition with an open-ended index ranging above and below zero for

TABLE 3. MINIMUM RAINFALL FOR 3-, 6-, 9-, AND 12-MO DURATIONS AND 2-, 3-, 5-, 10-, 20-, 30-, 50-, 100-, AND 200-YR RETURN PERIODS

RETURN PERIOD (yr)	RAINFALL (mm) Duration (mo) 3	6	9	12
Station 707				
2	85	249	488	850
3	76	221	433	744
5	67	194	379	643
10	57	166	322	535
20	49	142	275	446
30	45	130	250	399
50	40	115	222	345
100	34	97	186	279
200	29	81	154	217
Station 741				
2	17	83	222	423
3	13	63	177	352
5	9	44	133	284
10	5	24	87	211
20	2	7	49	151
30	1	0	29	120
50	0	0	5	84
100	0	0	0	39
200	0	0	0	0
Station 782				
2	427	1179	2129	3168
3	383	1057	1890	2827
5	341	941	1661	2501
10	295	816	1415	2151
20	258	713	1213	1863
30	239	659	1107	1712
50	216	597	985	1538
100	188	519	833	1322
200	163	449	694	1124
Station 794				
2	80	259	558	936
3	71	218	486	824
5	62	179	417	717
10	53	137	343	602
20	45	102	282	507
30	41	84	251	457
50	37	63	214	400
100	31	37	169	329
200	26	13	127	264
Station 798				
2	13	81	207	402
3	9	62	162	329
5	6	44	119	259
10	2	25	72	184
20	0	9	34	123
Station 798—*Continued*				
30	0	1	14	90
50	0	0	0	53
100	0	0	0	7
200	0	0	0	0
Station 847				
2	39	150	343	662
3	33	122	288	565
5	26	94	235	473
10	20	65	178	374
20	14	41	131	292
30	11	28	106	249
50	8	14	78	200
100	4	0	43	138
200	0	0	10	82
Station 863				
2	96	274	554	955
3	86	243	482	838
5	77	213	414	727
10	68	181	340	607
20	60	155	280	508
30	56	141	248	457
50	51	125	212	397
100	45	106	166	323
200	40	88	125	256
Station 883				
2	823	2204	3855	5583
3	751	2007	3489	5097
5	682	1818	3140	4633
10	609	1617	2766	4136
20	548	1450	2457	3726
30	517	1363	2297	3512
50	480	1263	2110	3264
100	435	1138	1878	2956
200	393	1023	1666	2675
Station 912				
2	91	267	527	877
3	81	234	456	772
5	71	203	389	673
10	61	169	317	566
20	53	142	258	477
30	49	128	227	431
50	44	111	191	378
100	37	90	147	312
200	32	71	106	251

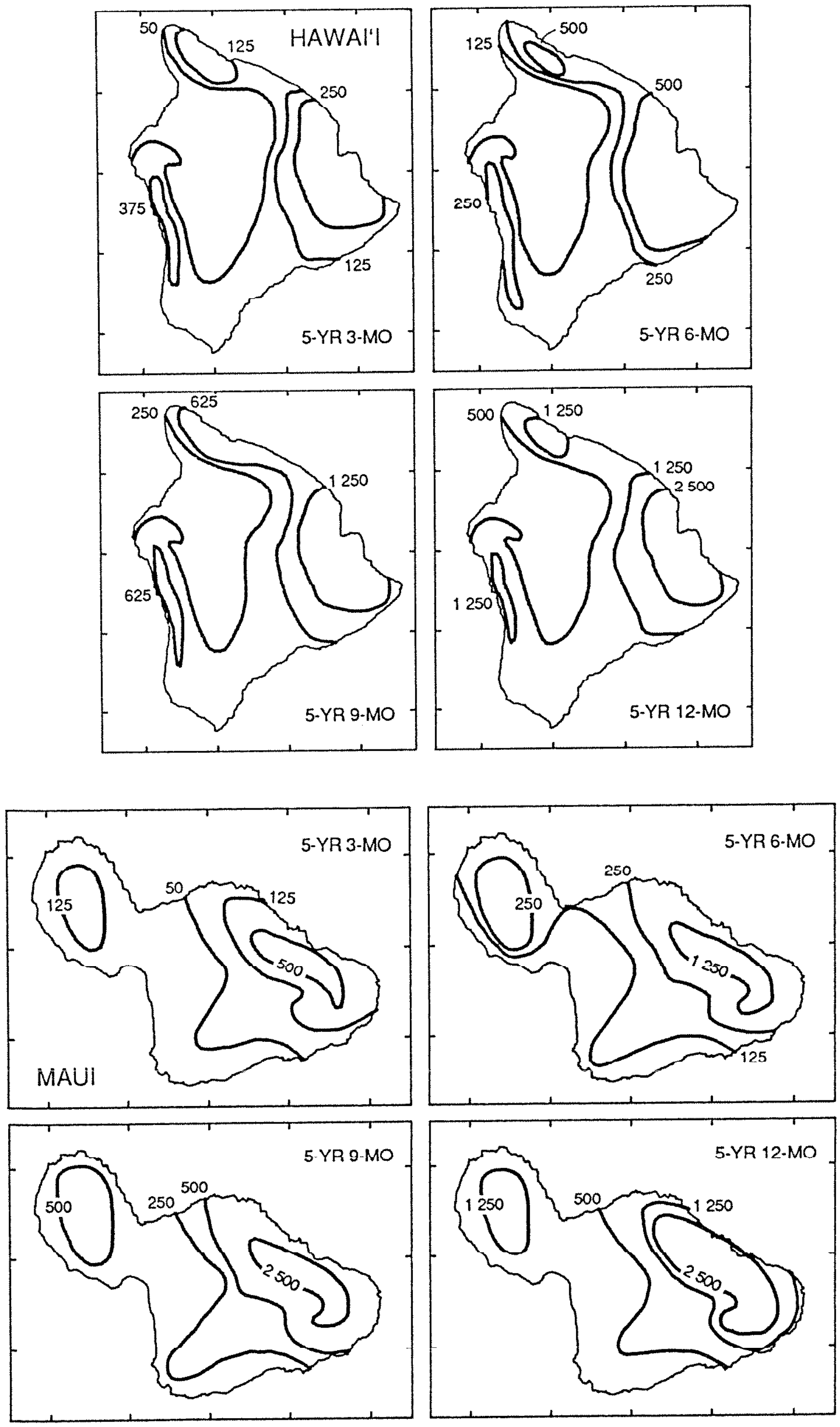


Figure 8. Minimum rainfall, 3-, 6-, 9-, and 12-mo durations, 5-yr return period for six major islands

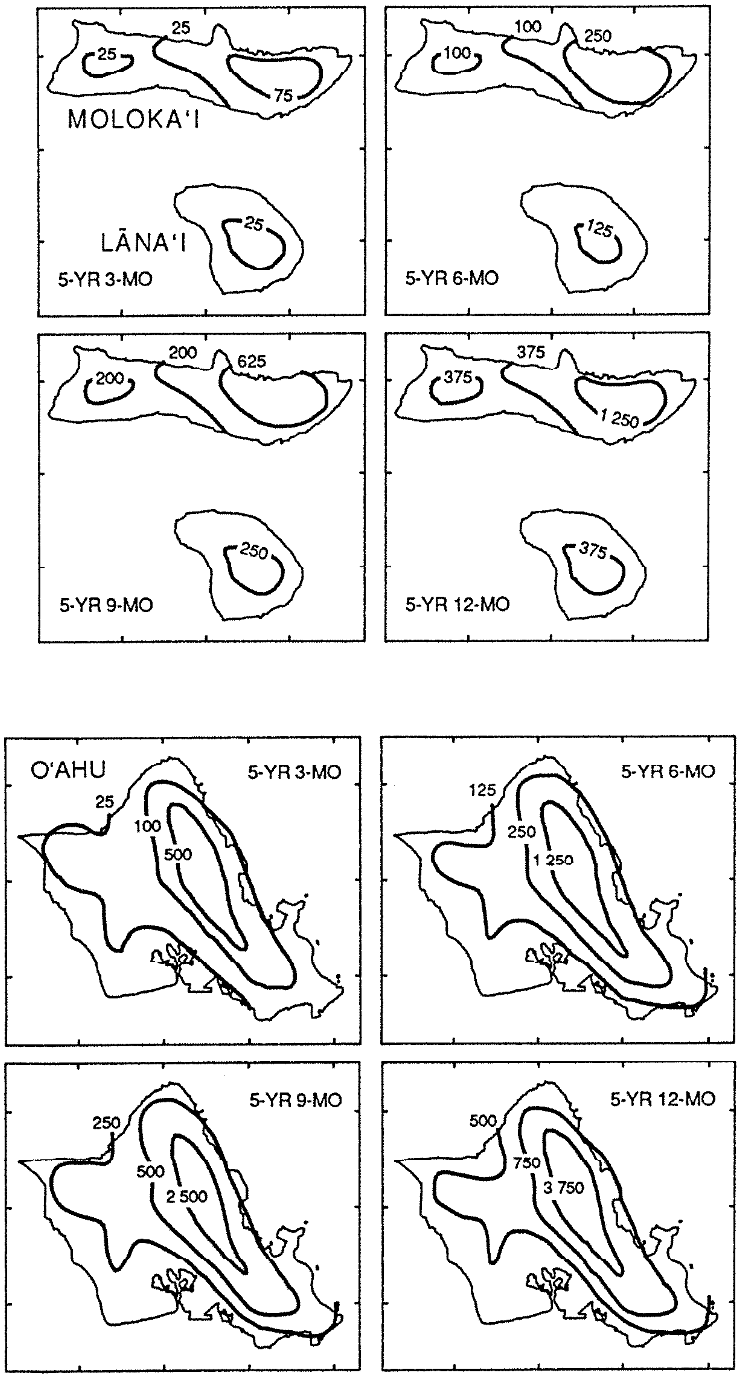


Figure 8.—*Continued*

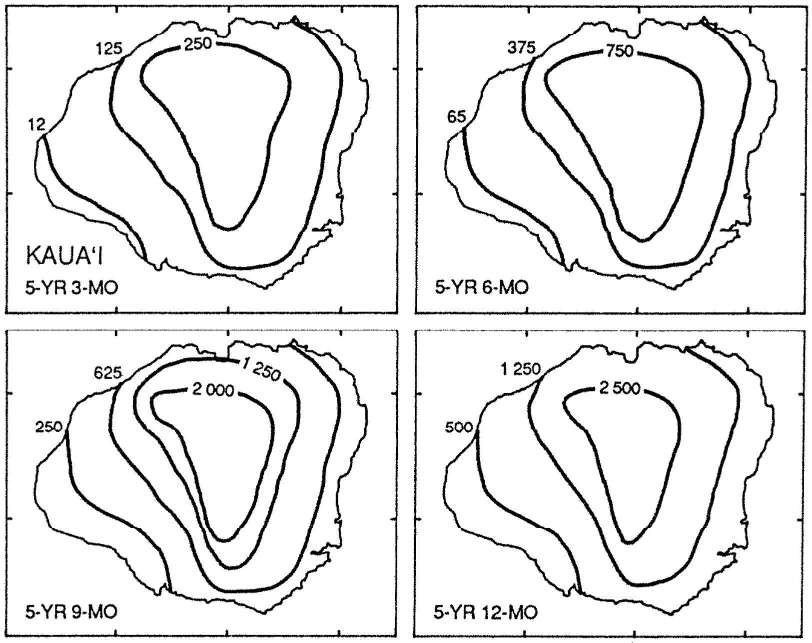


Figure 8.—*Continued*

respective wet and dry conditions (Table 4). But while the PDSI is based on a water balance calculation, the BMDI uses only monthly rainfall.

Calculation of the BMDI at each station consists of determining the standardized monthly rainfall departures, the moisture index (M), from which the time series of drought intensity index (I) is computed. A complete description of the BMDI method is given in Appendix A. Monthly values of I are interpreted according to Table 4.

Monthly state and island BMDI values were computed as the mean of individual station values for a given month and are shown as time series plots in Figure 9. Because of the compressed time scale, the individual dry and wet spells are difficult to see in this graph. The same time series are reproduced with an expanded time scale in Appendix Figures D.6–D.12, allowing dry and wet spells for the state and for individual islands to be identified clearly.

While monthly BMDI time series are rather noisy, we can see the major dry and wet periods by computing annual averages. Figure 10 gives the annual BMDI time series for the state and for each island. Each bar represents the mean of individual monthly BMDI values at all network stations. The similarity among time series for different islands is indicative of the large spatial scale of major events. Examining the time series for the entire state (Fig. 10), the years 1953, 1984, 1912, 1897, 1933, and 1973 stand out as the driest years during the series. It is also noteworthy that runs of below-zero index never exceed 5 years.

TABLE 4. PALMER DROUGHT SEVERITY INDEX OR BHALME AND MOOLEY DROUGHT INDEX DEFINITIONS

Index			Moisture Condition
4.00	or	greater	extremely wet
3.00	to	3.99	very wet
2.00	to	2.99	moderately wet
1.00	to	1.99	slightly wet
0.99	to	-0.99	near normal
-1.00	to	-1.99	mild drought
-2.00	to	-2.99	moderate drought
-3.00	to	-3.99	severe drought
-4.00	or	less	extreme drought

Drought Area Index

Indices, such as PDSI and BMDI are often used to compute a secondary index based on the areal extent of drought. The DAI is computed for a predefined region as the proportion of the area with a severity index (e.g., BMDI) below some threshold. By assuming that each station represents approximately the same proportion of the state, the index can be calculated from the percentage of stations below the threshold. For example, using the BMDI to compute the DAI for moderate drought on Kaua'i, the percentage of network stations on the island with a drought intensity index (I) of -2 or less is determined for each month. For severe and extreme droughts, respective thresholds of -3 and -4 are selected. In Figure 11 are the time series of statewide DAI for (a) moderate, (b) severe, and (c) extreme drought. Again for better temporal resolution, see the expanded-time-scale plots in Appendix Figures D.13, D.14, and D.15.

Identifying Specific Historical Drought Events

Calculation of the BMDI enables us to identify specific meteorological drought events that have occurred in the state of Hawai'i, on each island, and at individual stations. To do so, however, requires that we adopt an operational definition of drought. The earlier discussion of drought definition concluded that an operational definition of drought applicable—everywhere and suitable for all purposes—will never be developed. Nevertheless, we sought to identify droughts in Hawai'i in a manner consistent with the general conceptual definition of drought.

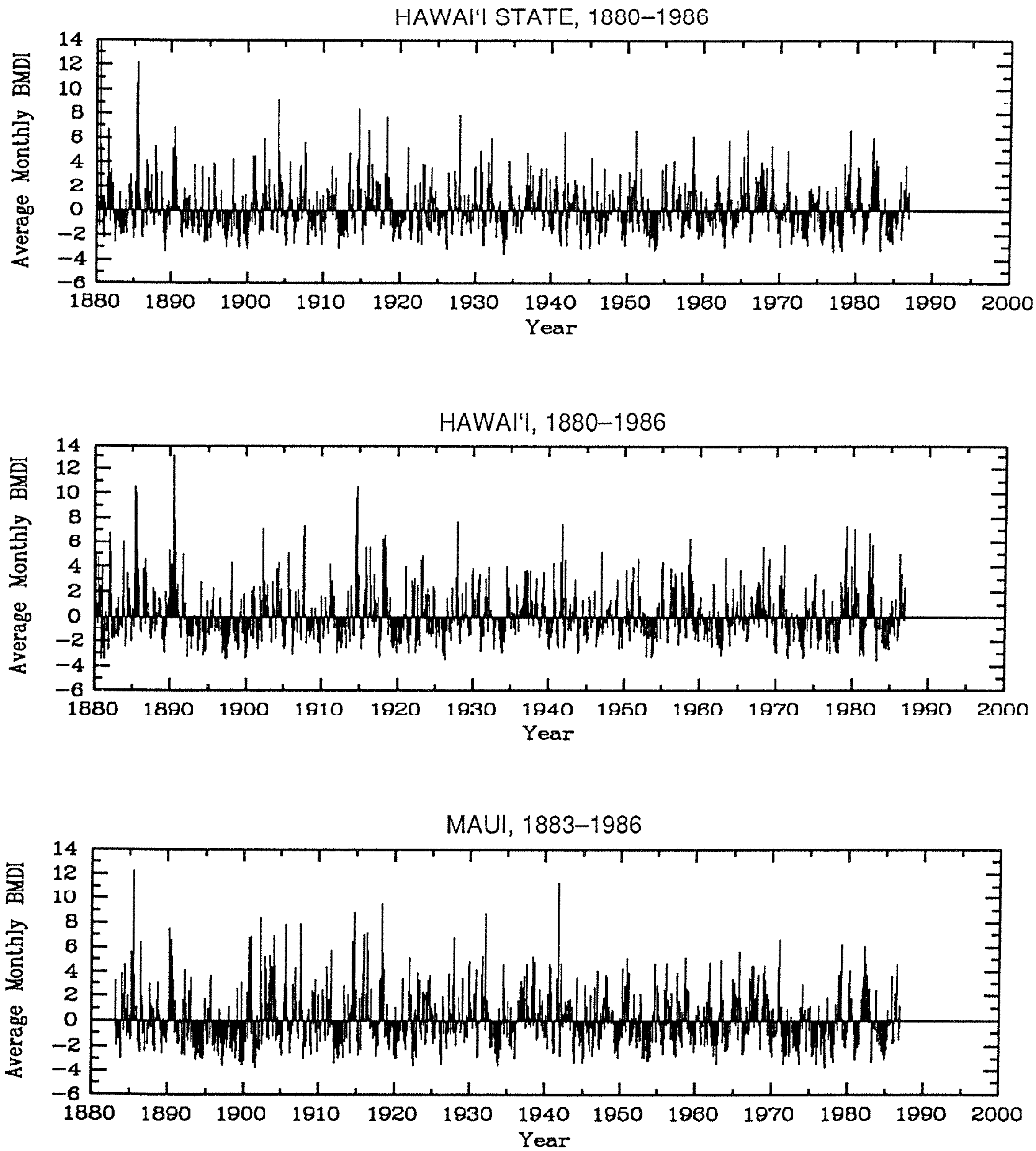
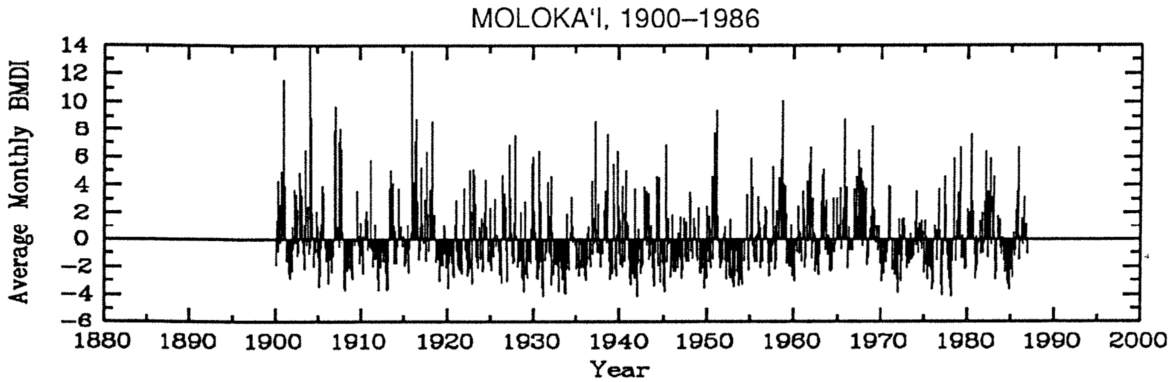
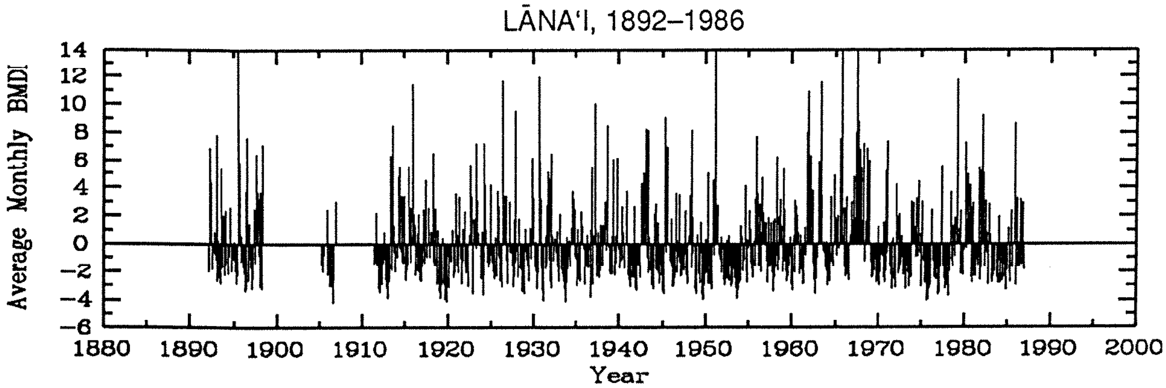


Figure 9. Average monthly BMDI for Hawai'i State and six major islands





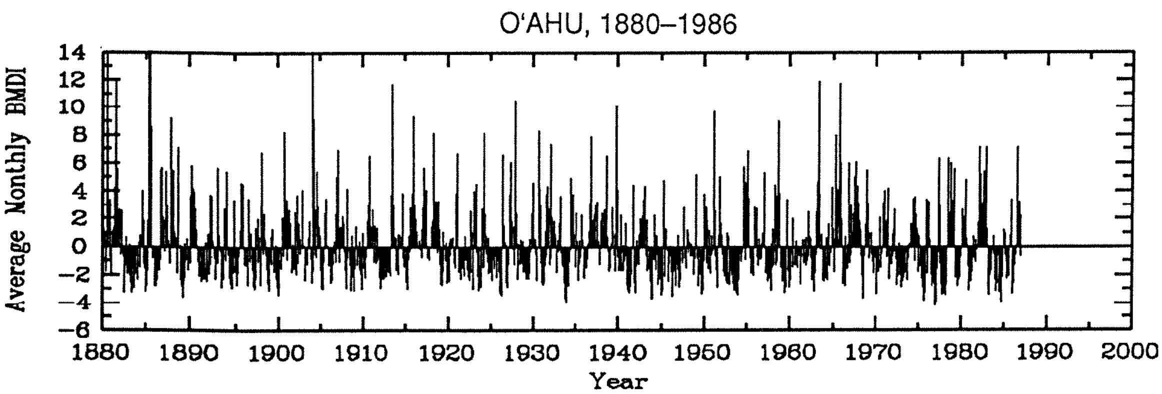


Figure 9.—*Continued*

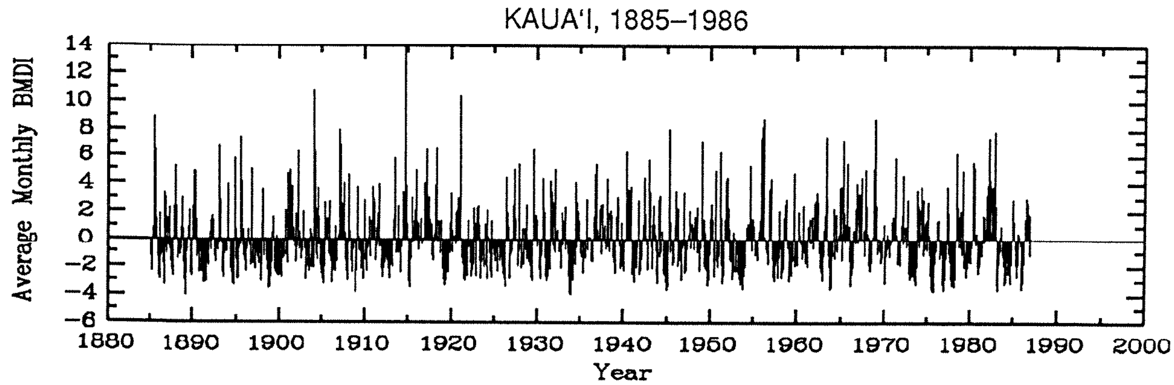


Figure 9.—*Continued*

Until now, our analysis of drought has been done without reference to a specific definition of drought. While the BMDI is an index of relative drought (and moist conditions), a set of criteria defining the beginning and end of drought events is necessary in order to use the index as part of an operational drought definition.

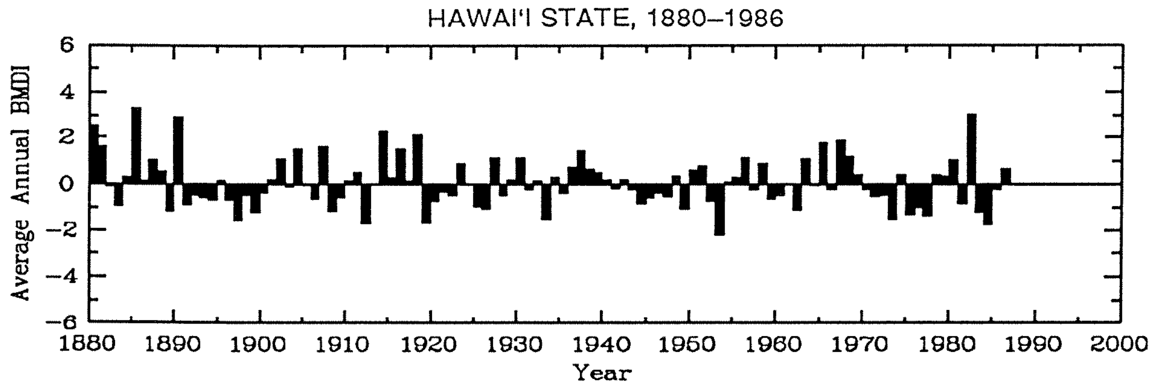
Given a time- and space-dependent index of the moisture condition, drought definition amounts to identifying the onset and termination of each event. Criteria for these decisions can be reduced to three variables: (1) threshold, the index value below which drought conditions exist; (2) minimum duration, the minimum period for which the index must be below the threshold for a drought event to exist; and (3) maximum break, the maximum allowable period within a drought during which the index is above the threshold.

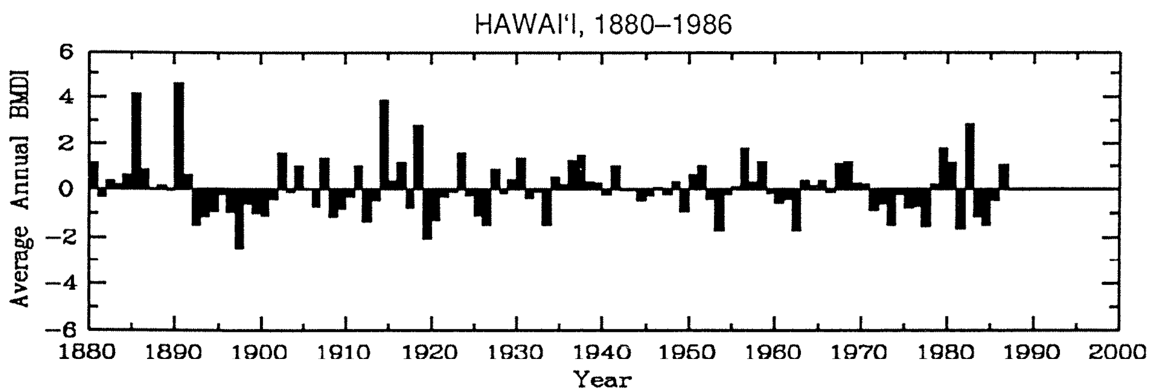
Threshold selection is somewhat arbitrary. By choosing a very low threshold, only intense droughts will be identified, while prolonged low intensity dry periods will be ignored. A high threshold may allow long periods of near normal conditions to become part of a drought event. We selected a BMDI threshold of -2 for this study, the same level used by Bhalme and Mooley (1980) for their DAI.

The impact of dryness is cumulative, making very brief dry periods relatively unimportant. The minimum duration requirement prevents these brief dry spells from being named as drought events. We selected a minimum duration of 2 months.

During most drought events, one or more brief breaks occur which, while providing temporary relief from some impacts, are eventually made unimportant by a rapid return to dry conditions. Recognizing that extended drought prior to a break is likely to have continuing cumulative impacts after a break, we allow 1-month breaks during existing droughts, provided that it is both preceded and followed by at least 2 months below the threshold.

Following Dracup, Lee, and Paulson (1980*a*), once the beginning and ending dates of an event are identified and the duration (D) is known, severity (S) can be computed as the sum of





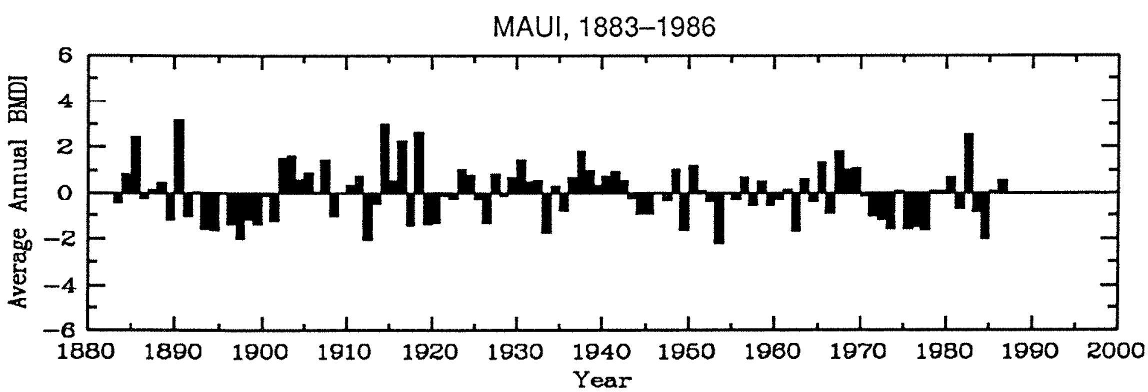


Figure 10. Average annual BMDI for Hawai'i State and six major islands

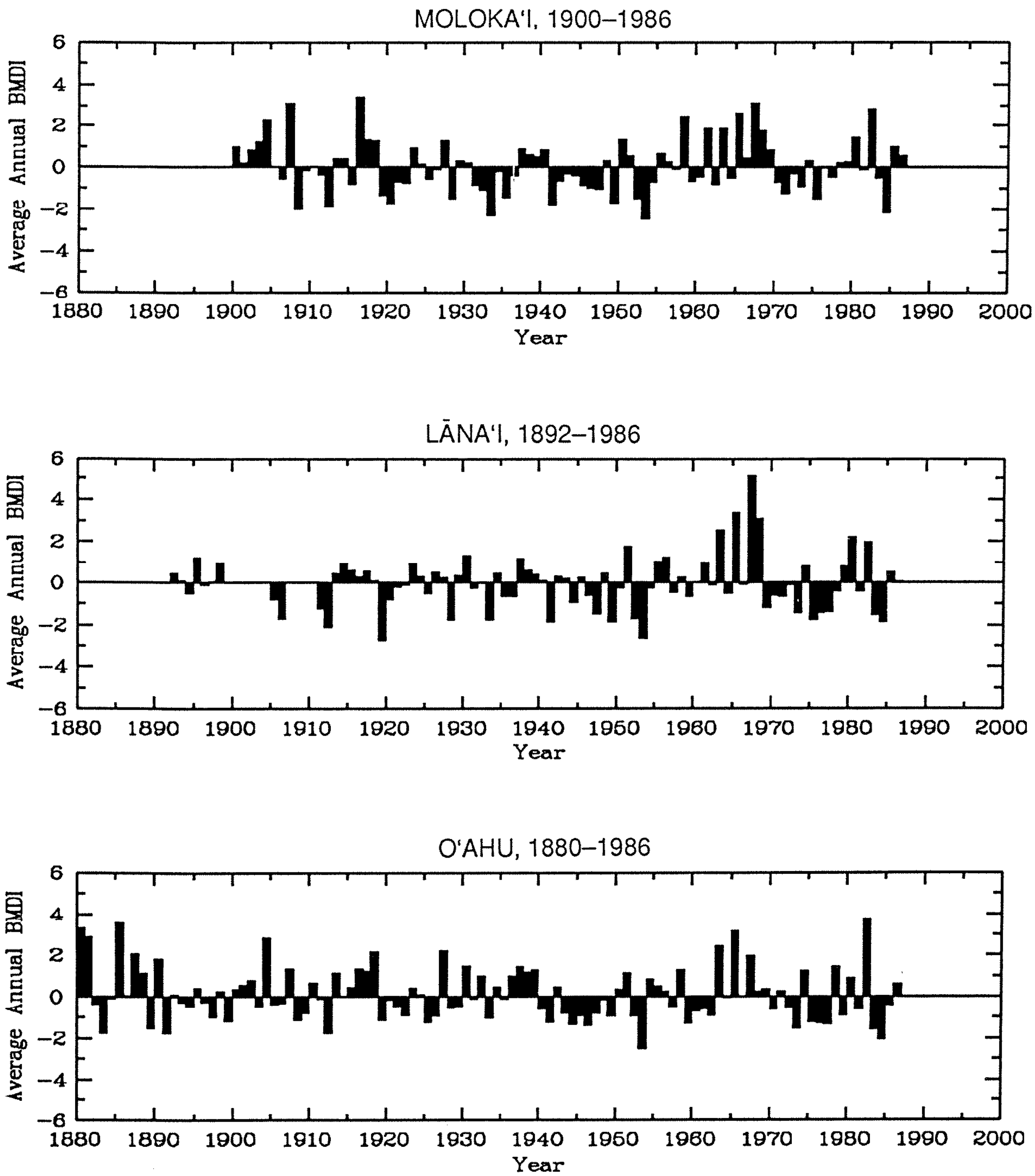


Figure 10.—*Continued*

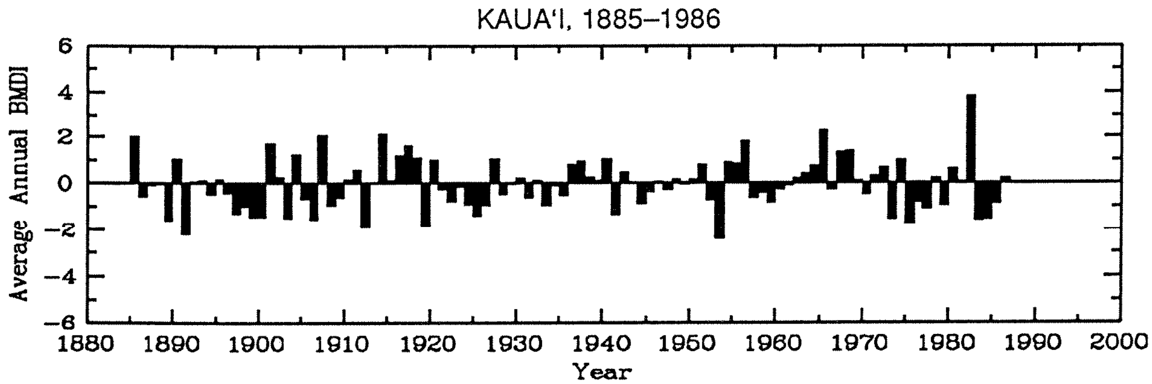


Figure 10.—*Continued*

the monthly index values during the period and Magnitude (M) is M = S/D. If the number of stations used in the computation is the same, severity can be compared among different events and droughts can be ranked on this basis. As the number of stations used to compute the average BMDI increases, there is a decrease in probability of the averaged index being below the threshold.

The definition just described can be applied to the monthly BMDI time series for each station or to the monthly values averaged for each island or the entire state. To apply the definition to an island, the BMDI averaged over the island is used. Areal extent of drought is automatically taken into consideration, since the island index will be lower if a greater number of stations are experiencing drought. The same is true in calculating statewide droughts.

Statewide Drought Events

In Table 5, all statewide drought events are listed in order of severity with the most severe events first. The upper part of the table lists events for which the entire rain-gage network was in operation. Because the severity statistic for drought events is affected by the number of stations used, events prior to February 1931 are listed separately at the bottom. We elected not to identify events before January 1895, when less than half the network was operating. The most severe statewide drought began in September 1977 and lasted 6 months. The most intense event (greatest negative magnitude) occurred between December 1976 and February 1977. Duration rather than magnitude tends to dominate the overall severity ranking. The longest statewide drought event, according to our definition, was 6 months, and most events lasted less than 4 months. The overall drought recurrence interval for the state is about 3.3 years.

To graphically depict the droughts in Table 5, bars representing each event were plotted along the time axis, with duration and magnitude indicated respectively by width and length

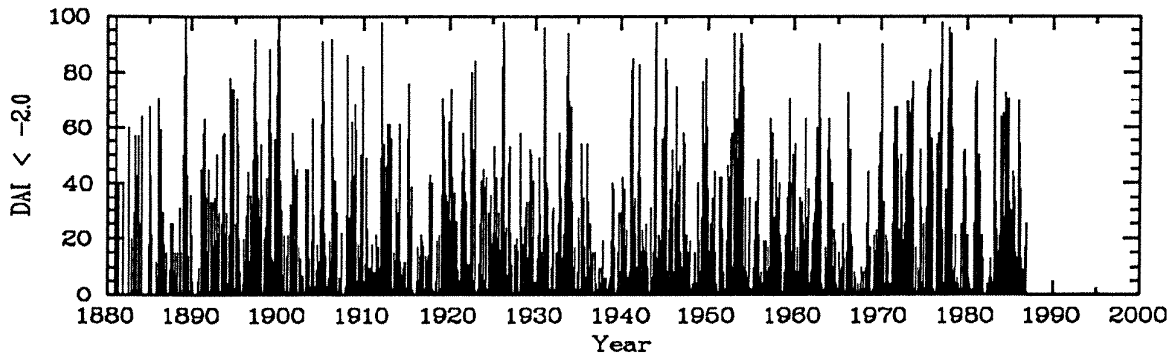


Figure 11.a. Monthly drought area index for moderate drought (% of stas. with < -2.0 BMDI), Hawai'i State

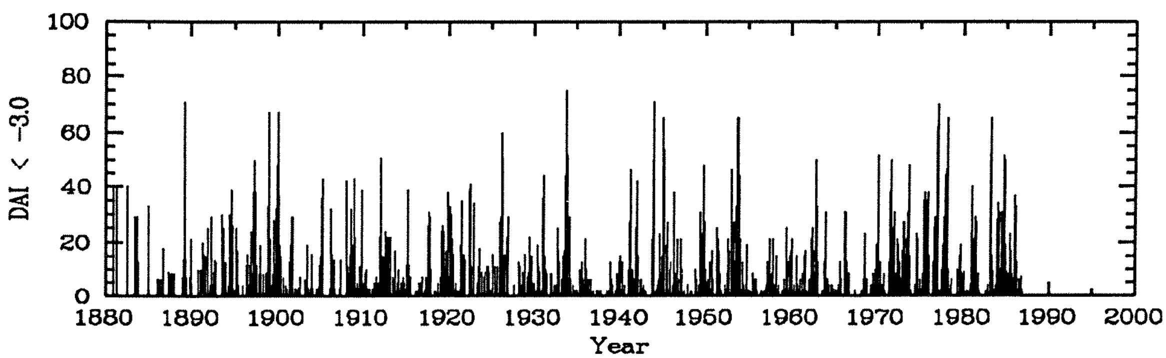


Figure 11.b. Monthly drought area index for severe drought (% of stas. with < -3.0 BMDI), Hawai'i State

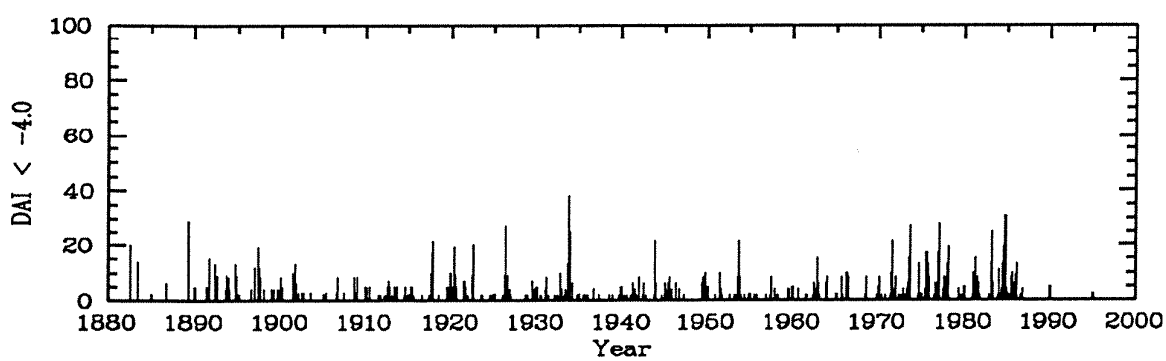


Figure 11.c. Monthly drought area index for extreme drought (% of stas. with < -4.0 BMDI), Hawai'i State

TABLE 5. RANKED DROUGHT EVENTS, HAWAI'I STATE

EVENT RANK	DROUGHT EVENT From		To		SEVERITY	MAGNITUDE	DURATION (mo)
COMPLETE RAIN-GAGE NETWORK, FEBRUARY 1931 TO DECEMBER 1986							
1	1977	Sep	1978	Feb	-16.22	-2.70	6
2	1975	May	1975	Oct	-14.85	-2.48	6
3	1953	July	1953	Nov	-14.29	-2.86	5
4	1933	Aug	1933	Nov	-11.61	-2.90	4
5	1976	Dec	1977	Feb	-8.97	-2.99	3
6	1943	Nov	1944	Jan	-8.47	-2.82	3
7	1983	Feb	1983	Apr	-8.33	-2.78	3
8	1984	Aug	1984	Oct	-7.63	-2.54	3
9	1941	Feb	1941	Apr	-7.54	-2.51	3
10	1973	June	1973	Aug	-7.45	-2.48	3
11	1945	Jan	1945	Feb	-5.80	-2.90	2
12	1949	Sep	1949	Oct	-5.57	-2.78	2
13	1962	Nov	1962	Dec	-5.19	-2.59	2
14	1971	July	1971	Aug	-4.99	-2.50	2
15	1973	Jan	1973	Feb	-4.42	-2.21	2
16	1949	Apr	1949	May	-4.32	-2.16	2
17	1952	Aug	1952	Sep	-4.10	-2.05	2
INCOMPLETE RAIN-GAGE NETWORK (MIN. 50% OF NETWORK), JANUARY 1895 TO JANUARY 1931							
1	1926	Jan	1926	May	-14.28	-2.86	5
2	1897	Jan	1897	May	-11.83	-2.37	5
3	1898	Nov	1899	Feb	-9.86	-2.47	4
4	1931	Jan	1931	Mar	-8.19	-2.73	3
5	1899	Nov	1900	Jan	-8.09	-2.70	3
6	1905	Jan	1905	Mar	-7.37	-2.46	3
7	1919	Feb	1919	Apr	-6.68	-2.23	3
8	1922	June	1922	July	-5.07	-2.54	2
9	1906	Feb	1906	Mar	-4.83	-2.41	2
10	1912	Aug	1912	Sep	-4.21	-2.11	2

(Fig. 12a). The area of each bar (duration x magnitude) represents severity. This graph makes it apparent that the 1970s and early 1980s were very drought-prone years. A total of eight statewide drought events occurred during the most recent 16-year period of study (1971–86). Such clusters of events are not unprecedented. Four distinct periods since 1895, a total of 53 of 92 years, can be identified during which all but 3 of 27 drought events took place: 1897–1906, 1919–33, 1941–53, and 1971–86.

Island Drought Events

Table 6 lists drought events for the island of Hawai'i. These events are plotted in Figure 12b. The drought from December 1980 to July 1981 is clearly the longest and most severe event on Hawai'i island since February 1931. The event beginning in November 1896 is indicated as being longer and more severe, but must be considered separately because its severity is calculated from only 8 of the 15 network rain gage stations. The 3-month summer drought of 1973 ranks as the island's most intense event. From Figure 12b we can see that particularly drought-prone periods were the 1890s and 1900s, the late 1910s and early 1920s, and the period between 1969 and 1984 during which 8 events occurred.

On Maui (Table 7), the three most severe droughts (1971–1972, 1953–1954, 1984–1985) were remarkably similar in duration, season, and magnitude. All lasted 8 months beginning in June or July. The 3-month winter drought of 1976–1977 was Maui's most intense. Maui was especially prone to drought during the period between 1971 and 1985 when 10 drought events were experienced (Fig. 12c).

Forty-two droughts were identified on Moloka'i (Table 8). Of those, 28 occurred between 1919 and 1954 (Fig. 12d), one every 1.3 years on average. The most severe event began in April 1933 and lasted for 8 months. The winter drought of 1976–1977 was the island's most intense.

Because of its small areal extent, Lāna'i experiences more islandwide droughts than other islands. In Table 9, a total of 54 drought events are listed since February 1892. The most severe and prolonged event began in May 1975 and lasted 9 months. Beginning in April 1969, 17 events occurred on Lāna'i during a 17-year period (Fig. 12e). The island's most severe drought began in May 1975 and lasted 9 months. The most intense event was a 2-month drought beginning in January 1931.

The two longest islandwide droughts identified in this study occurred on O'ahu: 12 months beginning November 1983, and 10 months beginning April 1953 (Table 10). The January-to-May-1926 and August-to-November-1933 droughts rank as the island's most

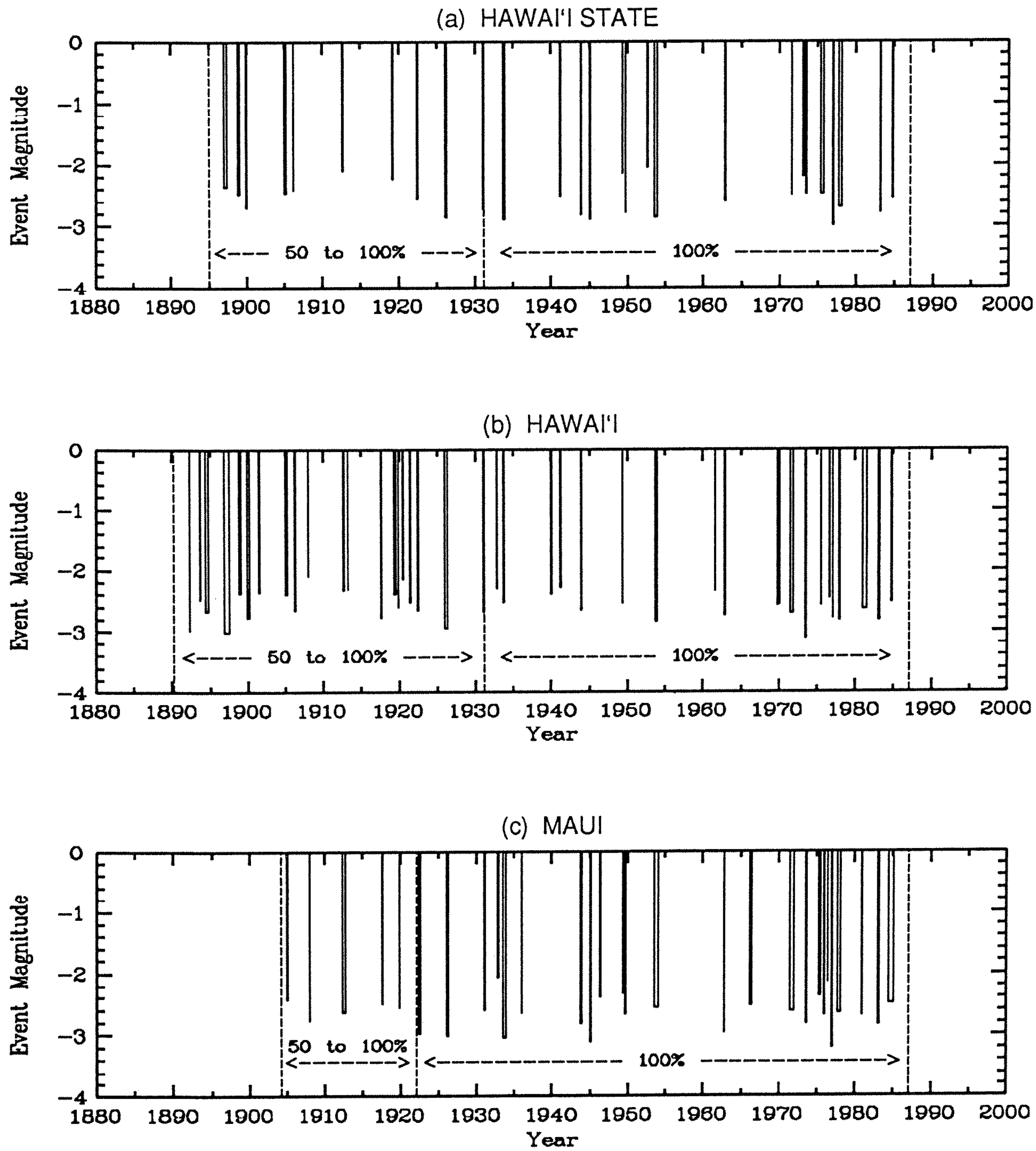


Figure 12. Drought event time plot for Hawai'i State and six major islands

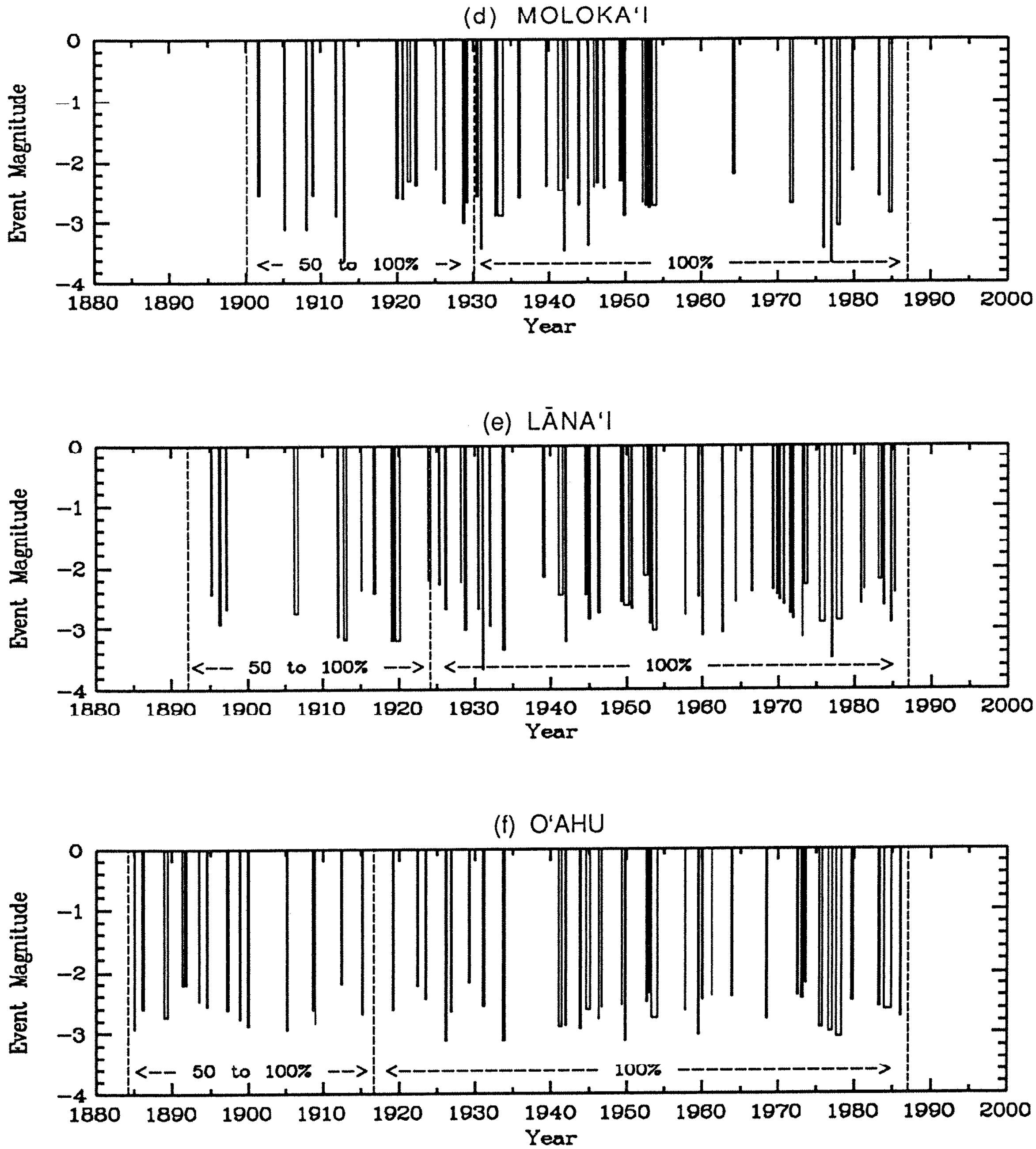


Figure 12.—*Continued*

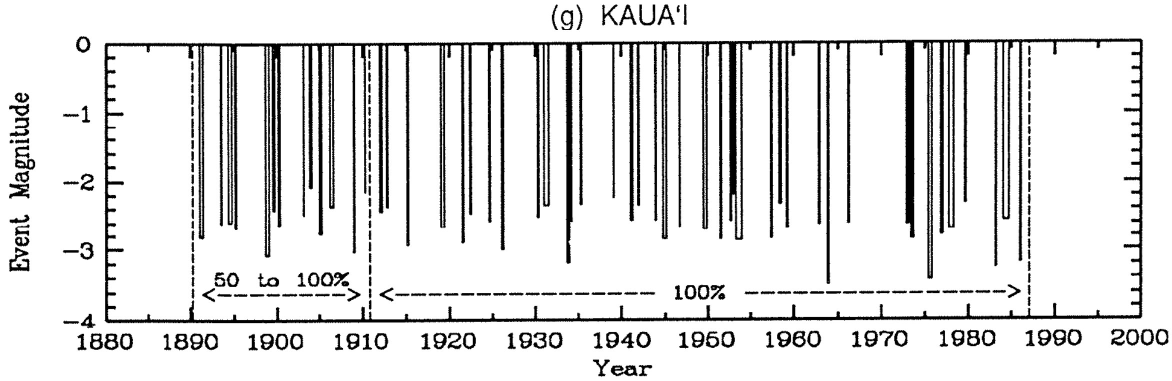


Figure 12.—*Continued*

intense. Between 1972 and 1986, 10 drought events are noted in Figure 12f. The 1920s and early 1930s as well as the 1940s and early 1950s were also drought-prone periods on O'ahu.

On Kaua'i, the three most severe droughts were April to November 1953, December 1983 to August 1984, and May to October 1975 (Table 11). The most intense event was the November-December-1963 drought. Droughts have been distributed rather uniformly in time, with the exception of the drought-free period of the late 1960s and early 1970s (Fig. 12g).

Regional Droughts

Drought events were also calculated for each of the 48 network stations. These regional droughts can be localized in the region of the station or embedded in islandwide or statewide events. Severity values for the individual stations tend to be much higher than those of the islands or the state, due to the relationship between severity and the number of stations used in the computation. By combining the droughts of all stations and ranking them on the basis of severity, the 120 most severe station droughts are identified in Table 12. The two most severe regional droughts identified by this study were both at Kahoma Intake (Sta. 374) on the leeward slopes of Pu'u Kukui on Maui from March 1971 to October 1973 (32 mo) and April 1911 to April 1913 (25 mo). In all, 1,974 regional droughts were identified. Using the average period of record of 91 years, we can deduce that about 22 regional droughts occur per year on average in Hawai'i.

Drought Duration and Seasonality

As defined in this study, droughts have a minimum length of 2 months and no prescribed upper limit. The frequency distributions of drought duration for the state and each island are shown in Figure 13. The longest islandwide drought was 12 months in duration on O'ahu.

TABLE 6. RANKED DROUGHT EVENTS, HAWAI'I

EVENT RANK	DROUGHT EVENTS From		To		SEVERITY	MAGNITUDE	DURATION (mo)
COMPLETE RAIN-GAGE NETWORK, FEBRUARY 1931 TO DECEMBER 1986							
1	1980	Dec	1981	July	-21.08	-2.64	8
2	1971	June	1971	Oct	-13.50	-2.70	5
3	1953	Aug	1953	Nov	-11.32	-2.83	4
4	1983	Jan	1983	Apr	-11.25	-2.81	4
5	1973	June	1973	Aug	-9.32	-3.11	3
6	1962	Oct	1962	Dec	-8.23	-2.74	3
7	1943	Nov	1944	Jan	-7.99	-2.66	3
8	1933	Aug	1933	Oct	-7.59	-2.53	3
9	1939	Dec	1940	Feb	-7.17	-2.39	3
10	1941	Feb	1941	Apr	-6.84	-2.28	3
11	1977	Nov	1977	Dec	-5.64	-2.82	2
12	1977	Jan	1977	Feb	-5.56	-2.78	2
13	1969	Oct	1969	Nov	-5.15	-2.57	2
14	1975	June	1975	July	-5.13	-2.57	2
15	1970	Feb	1970	Mar	-5.11	-2.56	2
16	1949	Apr	1949	May	-5.07	-2.54	2
17	1984	Sep	1984	Oct	-5.03	-2.52	2
18	1976	Aug	1976	Sep	-4.92	-2.46	2
19	1961	Aug	1961	Sep	-4.69	-2.35	2
20	1932	Oct	1932	Nov	-4.61	-2.30	2
INCOMPLETE RAIN-GAGE NETWORK (MIN. 50% OF NETWORK), FEBRUARY 1890 TO JANUARY 1931							
1	1896	Nov	1897	July	-27.08	-3.01	9
2	1925	Dec	1926	May	-17.69	-2.95	6
3	1894	May	1894	Oct	-16.01	-2.67	6
4	1899	Dec	1900	Apr	-13.82	-2.76	5
5	1904	Dec	1905	Apr	-11.96	-2.39	5
6	1919	Apr	1919	July	-9.60	-2.40	4
7	1898	Nov	1899	Feb	-9.53	-2.38	4
8	1920	May	1920	Aug	-8.63	-2.16	4
9	1917	July	1917	Sep	-8.32	-2.77	3
10	1931	Jan	1931	Mar	-8.07	-2.69	3
11	1906	Feb	1906	Apr	-7.97	-2.66	3
12	1893	Aug	1893	Oct	-7.42	-2.47	3
13	1901	June	1901	Aug	-7.12	-2.37	3
14	1892	Apr	1892	May	-5.94	-2.97	2
15	1922	June	1922	July	-5.30	-2.65	2
16	1919	Nov	1919	Dec	-5.22	-2.61	2
17	1921	May	1921	June	-5.04	-2.52	2
18	1912	Aug	1912	Sep	-4.67	-2.33	2
19	1913	Mar	1913	Apr	-4.62	-2.31	2
20	1907	Dec	1908	Jan	-4.22	-2.11	2

TABLE 7. RANKED DROUGHT EVENTS, MAUI

EVENT RANK	DROUGHT EVENTS From		To		SEVERITY	MAGNITUDE	DURATION (mo)
COMPLETE RAIN-GAGE NETWORK, JANUARY 1922 TO DECEMBER 1986							
1	1971	June	1972	Jan	-21.06	-2.63	8
2	1953	July	1954	Feb	-20.44	-2.55	8
3	1984	June	1985	Jan	-20.01	-2.50	8
4	1977	Sep	1978	Feb	-15.91	-2.65	6
5	1933	July	1933	Nov	-15.18	-3.04	5
6	1926	Feb	1926	May	-12.04	-3.01	4
7	1943	Oct	1944	Jan	-11.28	-2.82	4
8	1976	Dec	1977	Feb	-9.60	-3.20	3
9	1975	Apr	1975	July	-9.54	-2.38	4
10	1922	June	1922	Aug	-8.90	-2.97	3
11	1983	Jan	1983	Mar	-8.52	-2.84	3
12	1973	July	1973	Sep	-8.47	-2.82	3
13	1980	Nov	1981	Jan	-8.08	-2.69	3
14	1949	Aug	1949	Oct	-8.02	-2.67	3
15	1931	Jan	1931	Mar	-7.83	-2.61	3
16	1966	Apr	1966	June	-7.56	-2.52	3
17	1932	Oct	1932	Dec	-6.21	-2.07	3
18	1945	Jan	1945	Feb	-6.21	-3.10	2
19	1962	Oct	1962	Nov	-5.92	-2.96	2
20	1975	Dec	1976	Jan	-5.38	-2.69	2
21	1935	Dec	1936	Jan	-5.33	-2.66	2
22	1946	May	1946	June	-4.78	-2.39	2
23	1949	Apr	1949	May	-4.71	-2.35	2
24	1976	May	1976	June	-4.30	-2.15	2
INCOMPLETE RAIN-GAGE NETWORK (MIN. 50% OF NETWORK), FEBRUARY 1904 TO DECEMBER 1921							
1	1912	May	1912	Sep	-13.23	-2.64	5
2	1917	July	1917	Sep	-7.49	-2.50	3
3	1907	Dec	1908	Jan	-5.51	-2.76	2
4	1919	Nov	1919	Dec	-5.11	-2.55	2
5	1905	Jan	1905	Feb	-4.87	-2.43	2

TABLE 8. RANKED DROUGHT EVENTS, MOLOKA'I

EVENT RANK	DROUGHT EVENTS From		DROUGHT EVENTS To		SEVERITY	MAGNITUDE	DURATION (mo)
COMPLETE RAIN-GAGE NETWORK, FEBRUARY 1930 TO DECEMBER 1986							
1	1933	Apr	1933	Nov	-23.16	-2.89	8
2	1953	July	1954	Feb	-21.90	-2.74	8
3	1941	Feb	1941	Sep	-19.86	-2.48	8
4	1971	July	1972	Jan	-18.90	-2.70	7
5	1984	July	1984	Dec	-17.24	-2.87	6
6	1977	Oct	1978	Feb	-15.28	-3.06	5
7	1952	Dec	1953	Apr	-13.83	-2.77	5
8	1949	Sep	1949	Dec	-11.55	-2.89	4
9	1964	Feb	1964	June	-11.07	-2.21	5
10	1943	Oct	1944	Jan	-10.89	-2.72	4
11	1935	Nov	1936	Feb	-10.42	-2.61	4
12	1930	May	1930	Aug	-10.37	-2.59	4
13	1931	Jan	1931	Mar	-10.30	-3.43	3
14	1945	Jan	1945	Mar	-10.11	-3.37	3
15	1946	Mar	1946	June	-9.38	-2.35	4
16	1949	Mar	1949	June	-9.29	-2.32	4
17	1932	Nov	1933	Jan	-8.66	-2.89	3
18	1983	Mar	1983	May	-7.76	-2.59	3
19	1976	Dec	1977	Jan	-7.31	-3.66	2
20	1947	Feb	1947	Apr	-7.29	-2.43	3
21	1941	Dec	1942	Jan	-6.94	-3.47	2
22	1975	Dec	1976	Jan	-6.86	-3.43	2
23	1952	Aug	1952	Sep	-5.47	-2.73	2
24	1952	Mar	1952	Apr	-5.35	-2.68	2
25	1945	Oct	1945	Nov	-4.85	-2.42	2
26	1939	July	1939	Aug	-4.79	-2.39	2
27	1942	May	1942	June	-4.55	-2.27	2
28	1979	Sep	1979	Oct	-4.31	-2.16	2
INCOMPLETE RAIN-GAGE NETWORK (MIN. 50% OF NETWORK), FEBRUARY 1900 TO JANUARY 1930							
1	1928	Sep	1928	Dec	-12.05	-3.01	4
2	1921	May	1921	Sep	-11.55	-2.31	5
3	1912	Dec	1913	Feb	-10.90	-3.63	3
4	1926	Feb	1926	May	-10.70	-2.68	4
5	1919	Dec	1920	Mar	-10.41	-2.60	4
6	1901	Aug	1901	Nov	-10.24	-2.56	4
7	1908	Oct	1909	Jan	-10.22	-2.56	4
8	1922	May	1922	Aug	-9.53	-2.38	4
9	1907	Dec	1908	Feb	-9.29	-3.10	3
10	1911	Nov	1912	Jan	-8.67	-2.89	3
11	1905	Feb	1905	Mar	-6.19	-3.10	2
12	1929	Mar	1929	Apr	-5.36	-2.68	2
13	1920	Sep	1920	Oct	-5.27	-2.63	2
14	1925	Feb	1925	Mar	-4.25	-2.12	2

TABLE 9. RANKED DROUGHT EVENTS, LĀNA'I

EVENT RANK	DROUGHT EVENTS From		To		SEVERITY	MAGNITUDE	DURATION (mo)
COMPLETE RAIN-GAGE NETWORK, FEBRUARY 1924 TO DECEMBER 1986							
1	1975	May	1976	Jan	-26.07	-2.90	9
2	1977	Aug	1978	Mar	-22.92	-2.86	8
3	1953	May	1953	Nov	-21.28	-3.04	7
4	1949	Aug	1950	Mar	-21.00	-2.63	8
5	1941	Jan	1941	July	-17.10	-2.44	7
6	1928	Aug	1928	Dec	-15.11	-3.02	5
7	1944	Nov	1945	Mar	-14.15	-2.83	5
8	1952	Apr	1952	Sep	-12.78	-2.13	6
9	1973	June	1973	Oct	-11.47	-2.29	5
10	1983	Feb	1983	June	-11.03	-2.21	5
11	1946	Mar	1946	June	-10.97	-2.74	4
12	1926	Feb	1926	May	-10.67	-2.67	4
13	1976	Dec	1977	Feb	-10.51	-3.50	3
14	1933	Sep	1933	Nov	-10.05	-3.35	3
15	1959	Dec	1960	Feb	-9.37	-3.12	3
16	1952	Dec	1953	Feb	-8.72	-2.91	3
17	1938	Nov	1939	Feb	-8.63	-2.16	4
18	1949	Mar	1949	May	-7.69	-2.56	3
19	1931	Jan	1931	Feb	-7.36	-3.68	2
20	1969	Sep	1969	Nov	-7.33	-2.44	3
21	1941	Dec	1942	Jan	-6.45	-3.22	2
22	1973	Feb	1973	Mar	-6.31	-3.16	2
23	1962	Aug	1962	Sep	-6.17	-3.08	2
24	1931	Dec	1932	Jan	-5.87	-2.94	2
25	1984	Sep	1984	Oct	-5.77	-2.89	2
26	1971	Nov	1971	Dec	-5.66	-2.83	2
27	1957	Sep	1957	Oct	-5.54	-2.77	2
28	1971	June	1971	July	-5.49	-2.75	2
29	1950	Sep	1950	Oct	-5.35	-2.67	2
30	1930	May	1930	June	-5.34	-2.67	2
31	1983	Oct	1983	Nov	-5.27	-2.63	2
32	1970	Sep	1970	Oct	-5.21	-2.61	2
33	1980	Oct	1980	Nov	-5.19	-2.59	2
34	1964	May	1964	June	-5.12	-2.56	2
35	1970	Mar	1970	Apr	-5.06	-2.53	2
36	1959	June	1959	July	-4.94	-2.47	2
37	1944	July	1944	Aug	-4.90	-2.45	2
38	1985	Mar	1985	Apr	-4.83	-2.42	2
39	1966	July	1966	Aug	-4.81	-2.40	2
40	1969	Apr	1969	May	-4.74	-2.37	2

TABLE 9.—*Continued*

EVENT RANK	DROUGHT EVENTS From		To		SEVERITY	MAGNITUDE	DURATION (mo)
41	1981	Mar	1981	Apr	-4.72	-2.36	2
42	1925	Apr	1925	May	-4.52	-2.26	2
43	1928	Feb	1928	Mar	-4.48	-2.24	2
INCOMPLETE RAIN-GAGE NETWORK (MIN. 50% OF NETWORK), FEBRUARY 1892 TO JANUARY 1924							
1	1919	July	1920	Mar	-28.89	-3.21	9
2	1906	Feb	1906	Sep	-21.85	-2.73	8
3	1912	Sep	1913	Feb	-19.06	-3.18	6
4	1923	Oct	1924	Mar	-13.22	-2.20	6
5	1918	Dec	1919	Mar	-12.80	-3.20	4
6	1911	Nov	1912	Jan	-9.41	-3.14	3
7	1896	Apr	1896	June	8.76	-2.92	3
8	1897	Feb	1897	Apr	-8.01	-2.67	3
9	1916	Sep	1916	Nov	-7.26	-2.42	3
10	1895	Mar	1895	Apr	-4.86	-2.43	2
11	1915	Jan	1915	Feb	-4.71	-2.36	2

TABLE 10. RANKED DROUGHT EVENTS, O'AHU

EVENT RANK	DROUGHT EVENTS From		To		SEVERITY	MAGNITUDE	DURATION (mo)
COMPLETE RAIN-GAGE NETWORK, JULY 1916 TO DECEMBER 1986							
1	1983	Nov	1984	Oct	-31.48	-2.62	12
2	1953	Apr	1954	Jan	-27.55	-2.75	10
3	1977	Aug	1978	Mar	-24.49	-3.06	8
4	1944	Aug	1945	Mar	-20.94	-2.62	8
5	1976	Aug	1977	Feb	-20.84	-2.98	7
6	1975	May	1975	Oct	-17.55	-2.92	6
7	1926	Jan	1926	May	-15.63	-3.13	5
8	1943	Sep	1944	Jan	-14.63	-2.93	5
9	1941	Jan	1941	May	-14.45	-2.89	5
10	1933	Aug	1933	Nov	-12.53	-3.13	4
11	1983	Feb	1983	May	-10.31	-2.58	4
12	1931	Jan	1931	Apr	-10.21	-2.55	4
13	1979	July	1979	Oct	-9.90	-2.48	4
14	1973	Jan	1973	Apr	-9.76	-2.44	4
15	1949	Sep	1949	Nov	-9.36	-3.12	3
16	1968	June	1968	Aug	-8.30	-2.77	3
17	1985	Dec	1986	Feb	-8.20	-2.73	3
18	1959	Dec	1960	Feb	-7.38	-2.46	3
19	1923	June	1923	Aug	-7.34	-2.45	3
20	1959	June	1959	July	-6.05	-3.03	2
21	1941	Dec	1942	Jan	-5.76	-2.88	2
22	1946	Apr	1946	May	-5.51	-2.76	2
23	1926	Nov	1926	Dec	-5.33	-2.66	2
24	1957	Sep	1957	Oct	-5.29	-2.64	2
25	1919	Feb	1919	Mar	-5.25	-2.62	2
26	1946	Sep	1946	Oct	-5.19	-2.59	2
27	1949	Apr	1949	May	-5.07	-2.54	2
28	1952	Aug	1952	Sep	-5.00	-2.50	2
29	1963	Nov	1963	Dec	-4.83	-2.42	2
30	1972	July	1972	Aug	-4.81	-2.40	2
31	1961	Mar	1961	Apr	-4.80	-2.40	2
32	1952	Dec	1953	Jan	-4.74	-2.37	2
33	1922	June	1922	July	-4.48	-2.24	2
34	1973	Aug	1973	Sep	-4.40	-2.20	2
35	1929	Mar	1929	Apr	-4.37	-2.18	2

TABLE 10.—*Continued*

EVENT RANK	DROUGHT EVENTS From		To		SEVERITY	MAGNITUDE	DURATION (mo)
INCOMPLETE RAIN-GAGE NETWORK (MIN. 50% OF NETWORK), FEBRUARY 1884 TO JANUARY 1916							
1	1888	Dec	1889	May	-16.44	-2.74	6
2	1899	Nov	1900	Mar	-14.41	-2.88	5
3	1891	Mar	1891	Aug	-13.34	-2.22	6
4	1897	Feb	1897	May	-10.48	-2.62	4
5	1886	Jan	1886	Apr	-10.39	-2.60	4
6	1898	Nov	1899	Jan	-8.27	-2.76	3
7	1915	Jan	1915	Mar	-8.03	-2.68	3
8	1894	July	1894	Sep	-7.65	-2.55	3
9	1905	Feb	1905	Mar	-5.91	-2.95	2
10	1885	Jan	1885	Feb	-5.86	-2.93	2
11	1908	Nov	1908	Dec	-5.68	-2.84	2
12	1908	July	1908	Aug	-5.24	-2.62	2
13	1893	July	1893	Aug	-4.95	-2.48	2
14	1891	Nov	1891	Dec	-4.43	-2.22	2
15	1912	May	1912	June	-4.40	-2.20	2

TABLE 11. RANKED DROUGHT EVENTS, KAUA'I

EVENT RANK	DROUGHT EVENTS From		To		SEVERITY	MAGNITUDE	DURATION (mo)
COMPLETE RAIN-GAGE NETWORK, SEPTEMBER 1910 TO DECEMBER 1986							
1	1953	Apr	1953	Nov	-22.96	-2.87	8
2	1983	Dec	1984	Aug	-22.92	-2.55	9
3	1975	May	1975	Oct	-20.55	-3.43	6
4	1944	Sep	1945	Mar	-19.92	-2.85	7
5	1977	Sep	1978	Mar	-18.81	-2.69	7
6	1931	Jan	1931	July	-16.46	-2.35	7
7	1919	Jan	1919	June	-16.03	-2.67	6
8	1976	Oct	1977	Feb	-13.96	-2.79	5
9	1949	July	1949	Nov	-13.50	-2.70	5
10	1933	Aug	1933	Nov	-12.72	-3.18	4
11	1926	Feb	1926	May	-12.00	-3.00	4
12	1973	June	1973	Sep	-11.40	-2.85	4
13	1941	Jan	1941	Apr	-10.23	-2.56	4
14	1983	Feb	1983	Apr	-9.76	-3.25	3
15	1911	Dec	1912	Mar	-9.70	-2.43	4
16	1985	Dec	1986	Feb	-9.54	-3.18	3
17	1958	Mar	1958	June	-9.34	-2.33	4
18	1915	Jan	1915	Mar	-8.80	-2.93	3
19	1972	Dec	1973	Feb	-7.88	-2.63	3
20	1966	Mar	1966	May	-7.84	-2.61	3
21	1943	Nov	1944	Jan	-7.69	-2.56	3
22	1912	Sep	1912	Nov	-7.08	-2.36	3
23	1963	Nov	1963	Dec	-6.98	-3.49	2
24	1979	July	1979	Sep	-6.94	-2.31	3
25	1921	July	1921	Aug	-5.78	-2.89	2
26	1951	June	1951	July	-5.71	-2.85	2
27	1957	May	1957	June	-5.67	-2.84	2
28	1959	Mar	1959	Apr	-5.34	-2.67	2
29	1946	Sep	1946	Oct	-5.31	-2.66	2
30	1962	Nov	1962	Dec	-5.26	-2.63	2
31	1934	Feb	1934	Mar	-5.16	-2.58	2
32	1952	Aug	1952	Sep	-5.16	-2.58	2
33	1924	Aug	1924	Sep	-5.14	-2.57	2
34	1930	Apr	1930	May	-5.01	-2.51	2
35	1922	June	1922	July	-4.91	-2.46	2
36	1941	Dec	1942	Jan	-4.70	-2.35	2
37	1935	Apr	1935	May	-4.65	-2.33	2
38	1938	Dec	1939	Jan	-4.46	-2.23	2
39	1952	Dec	1953	Jan	-4.41	-2.21	2

TABLE 11.—*Continued*

EVENT RANK	DROUGHT EVENTS From		To		SEVERITY	MAGNITUDE	DURATION (mo)
INCOMPLETE RAIN-GAGE NETWORK (MIN. 50% OF NETWORK), JANUARY 1890 TO AUGUST 1910							
1	1898	Sep	1899	Feb	-18.45	-3.07	6
2	1894	May	1894	Oct	-15.53	-2.59	6
3	1906	Feb	1906	July	-14.20	-2.37	6
4	1891	Jan	1891	May	-14.09	-2.82	5
5	1905	Jan	1905	Apr	-11.05	-2.76	4
6	1900	Mar	1900	June	-10.49	-2.62	4
7	1908	Nov	1909	Jan	-9.10	-3.03	3
8	1895	Mar	1895	May	-8.05	-2.68	3
9	1899	July	1899	Sep	-7.26	-2.42	3
10	1903	Nov	1904	Jan	-6.28	-2.09	3
11	1893	July	1893	Aug	-5.20	-2.60	2
12	1903	Feb	1903	Mar	-4.96	-2.48	2
13	1910	Mar	1910	Apr	-4.33	-2.16	2

TABLE 12. HIGHEST RANKING REGIONAL DROUGHT EVENTS, HAWAI'I STATE

EVENT RANK	DROUGHT EVENTS From		To		SEVERITY	MAGNITUDE	DURATION (mo)	STATION No.
1	1971	Mar	1973	Oct	-101.14	-3.16	32	374.00
2	1911	Apr	1913	Apr	-85.17	-3.41	25	374.00
3	1932	Apr	1933	Oct	-78.62	-4.14	19	540.00
4	1976	June	1978	Feb	-72.09	-3.43	21	2.00
5	1952	Feb	1954	Jan	-62.73	-2.61	24	529.00
6	1913	Dec	1915	Aug	-62.26	-2.96	21	374.00
7	1952	Nov	1954	Aug	-58.02	-2.64	22	147.00
8	1907	Dec	1909	May	-57.67	-3.20	18	483.00
9	1983	Nov	1984	Oct	-56.09	-4.67	12	1051.00
10	1969	Mar	1970	June	-56.06	-3.50	16	2.00
11	1890	Aug	1891	Dec	-54.62	-3.21	17	1020.00
12	1919	Apr	1920	Aug	-53.12	-3.12	17	92.00
13	1956	Nov	1958	Feb	-52.88	-3.31	16	374.00
14	1912	Jan	1913	Apr	-52.00	-3.25	16	92.10
15	1896	Nov	1897	Dec	-49.41	-3.53	14	175.10
16	1972	Oct	1973	Oct	-48.90	-3.76	13	2.00
17	1971	May	1972	May	-48.35	-3.72	13	540.00
18	1983	Nov	1984	Nov	-44.31	-3.41	13	863.00
19	1919	June	1920	Aug	-43.97	-2.93	15	217.00
20	1896	Oct	1897	Dec	-43.83	-2.92	15	118.00
21	1971	May	1972	July	-43.65	-2.91	15	194.00
22	1952	Dec	1954	Jan	-42.92	-3.07	14	707.00
23	1899	June	1900	Sep	-42.86	-2.68	16	1020.00
24	1977	July	1978	Apr	-42.17	-4.22	10	883.00
25	1977	June	1978	Mar	-41.96	-4.20	10	73.20
26	1935	May	1936	Mar	-41.69	-3.79	11	540.00
27	1896	June	1897	June	-41.54	-3.20	13	782.00
28	1925	Dec	1926	Nov	-41.08	-3.42	12	142.00
29	1890	Dec	1891	Dec	-41.05	-3.16	13	1110.00
30	1925	Mar	1926	May	-40.87	-2.72	15	1110.00
31	1976	June	1977	Apr	-40.83	-3.71	11	883.00
32	1933	Apr	1934	Mar	-40.64	-3.39	12	782.00
33	1983	Dec	1984	Oct	-40.61	-3.69	11	782.00
34	1962	Jan	1963	Feb	-40.60	-2.90	14	194.00
35	1933	Apr	1934	Mar	-40.58	-3.38	12	350.00
36	1932	Nov	1933	Nov	-40.46	-3.11	13	562.00
37	1896	June	1897	Aug	-40.34	-2.69	15	65.00
38	1985	Apr	1986	Feb	-40.22	-3.66	11	1051.00
39	1944	Dec	1945	Dec	-39.97	-3.07	13	883.00
40	1973	Feb	1973	Sep	-39.75	-4.97	8	73.20
41	1953	Apr	1954	Jan	-39.21	-3.92	10	782.00
42	1893	Sep	1894	Oct	-38.80	-2.77	14	118.00

TABLE 12.—*Continued*

EVENT RANK	DROUGHT EVENTS From		To		SEVERITY	MAGNITUDE	DURATION (mo)	STATION No.
43	1913	Jan	1913	Oct	-38.28	-3.83	10	65.00
44	1981	Jan	1981	Nov	-38.15	-3.47	11	2.00
45	1941	Jan	1942	Jan	-37.46	-2.88	13	529.00
46	1962	Apr	1963	Mar	-37.39	-3.12	12	217.00
47	1896	Nov	1897	Sep	-37.38	-3.40	11	142.00
48	1983	Jan	1983	Nov	-37.33	-3.39	11	2.00
49	1971	May	1972	June	-37.32	-2.67	14	217.00
50	1890	Dec	1891	Dec	-37.07	-2.85	13	912.00
51	1973	Feb	1973	Nov	-37.06	-3.71	10	92.10
52	1919	June	1920	July	-37.01	-2.64	14	103.00
53	1984	Apr	1985	Feb	-36.64	-3.33	11	194.00
54	1953	Jan	1954	Feb	-36.44	-2.60	14	354.00
55	1977	July	1978	Mar	-36.43	-4.05	9	782.00
56	1933	Feb	1934	Apr	-36.11	-2.41	15	147.00
57	1945	Jan	1945	Dec	-35.94	-2.99	12	782.00
58	1911	Nov	1912	Nov	-35.91	-2.76	13	863.00
59	1953	Mar	1954	Apr	-35.89	-2.56	14	217.00
60	1917	Apr	1917	Dec	-35.60	-3.96	9	175.00
61	1972	Dec	1973	Oct	-35.47	-3.22	11	1134.00
62	1976	June	1977	Feb	-35.25	-3.92	9	782.00
63	1962	Jan	1962	Dec	-35.11	-2.93	12	333.00
64	1984	July	1985	Mar	-34.87	-3.87	9	540.00
65	1962	Apr	1963	Mar	-34.65	-2.89	12	118.00
66	1896	Nov	1897	Oct	-34.15	-2.85	12	217.00
67	1905	Dec	1906	Nov	-34.08	-2.84	12	1134.00
68	1933	July	1934	Apr	-33.91	-3.39	10	92.00
69	1917	Feb	1918	Jan	-33.80	-2.82	12	374.00
70	1960	Jan	1960	Nov	-33.62	-3.06	11	2.00
71	1919	June	1920	Mar	-33.28	-3.33	10	650.00
72	1952	Dec	1953	Nov	-33.27	-2.77	12	965.00
73	1980	Nov	1981	July	-33.19	-3.69	9	142.00
74	1984	Feb	1984	Nov	-33.17	-3.32	10	2.00
75	1975	Apr	1975	Dec	-32.98	-3.66	9	1115.00
76	1980	Nov	1981	Aug	-32.86	-3.29	10	350.00
77	1975	May	1976	Jan	-32.55	-3.62	9	684.00
78	1972	May	1973	Jan	-32.46	-3.61	9	782.00
79	1984	Mar	1984	Nov	-32.39	-3.60	9	103.00
80	1899	Aug	1900	Aug	-32.32	-2.49	13	1110.00
81	1949	Apr	1949	Dec	-32.26	-3.58	9	782.00
82	1975	Apr	1976	Feb	-32.12	-2.92	11	194.00
83	1899	Aug	1900	May	-32.05	-3.20	10	21.00
84	1977	July	1978	Apr	-31.98	-3.20	10	1051.00

TABLE 12.—*Continued*

EVENT RANK	DROUGHT EVENTS From		To		SEVERITY	MAGNITUDE	DURATION (mo)	STATION No.
85	1919	Sep	1920	July	-31.95	-2.90	11	194.00
86	1919	Nov	1920	Aug	-31.58	-3.16	10	350.00
87	1953	Apr	1954	Jan	-31.32	-3.13	10	1115.00
88	1971	May	1972	Jan	-31.27	-3.47	9	406.00
89	1953	Apr	1953	Nov	-31.23	-3.90	8	1051.00
90	1972	Dec	1973	Sep	-31.21	-3.12	10	1020.00
91	1984	June	1985	Jan	-30.93	-3.87	8	442.00
92	1917	Feb	1917	Oct	-30.81	-3.42	9	217.00
93	1977	June	1978	Mar	-30.75	-3.08	10	250.00
94	1925	Dec	1926	July	-30.74	-3.84	8	92.00
95	1980	Nov	1981	Aug	-30.74	-3.07	10	406.00
96	1925	Sep	1926	May	-30.72	-3.41	9	782.00
97	1890	Dec	1891	Dec	-30.50	-2.35	13	741.00
98	1944	June	1945	Mar	-30.34	-3.03	10	483.00
99	1980	Nov	1981	July	-30.18	-3.35	9	92.00
100	1985	Apr	1985	Oct	-30.06	-4.29	7	2.00
101	1944	July	1945	Mar	-30.04	-3.34	9	847.00
102	1952	Dec	1953	Nov	-30.01	-2.50	12	690.00
103	1925	Nov	1926	July	-29.82	-3.31	9	54.00
104	1953	Apr	1954	Jan	-29.82	-2.98	10	1020.00
105	1925	Dec	1926	July	-29.80	-3.72	8	65.00
106	1908	May	1909	Jan	-29.63	-3.29	9	14.00
107	1984	June	1985	Jan	-29.62	-3.70	8	406.00
108	1976	May	1977	Mar	-29.55	-2.69	11	741.00
109	1953	June	1954	Feb	-29.40	-3.27	9	483.00
110	1966	Mar	1966	Sep	-29.38	-4.20	7	782.00
111	1940	Dec	1941	Aug	-29.26	-3.25	9	707.00
112	1912	Aug	1913	Apr	-29.17	-3.24	9	103.00
113	1885	Oct	1886	Aug	-29.14	-2.65	11	21.00
114	1959	Sep	1960	July	-29.12	-2.65	11	92.10
115	1971	June	1972	Jan	-29.10	-3.64	8	442.00
116	1975	May	1976	Jan	-29.03	-3.23	9	883.00
117	1953	May	1954	Jan	-29.01	-3.22	9	863.00
118	1977	Oct	1978	July	-28.80	-2.88	10	374.00
119	1973	Jan	1973	Oct	-28.77	-2.88	10	650.00
120	1908	May	1909	Jan	-28.58	-3.18	9	21.00

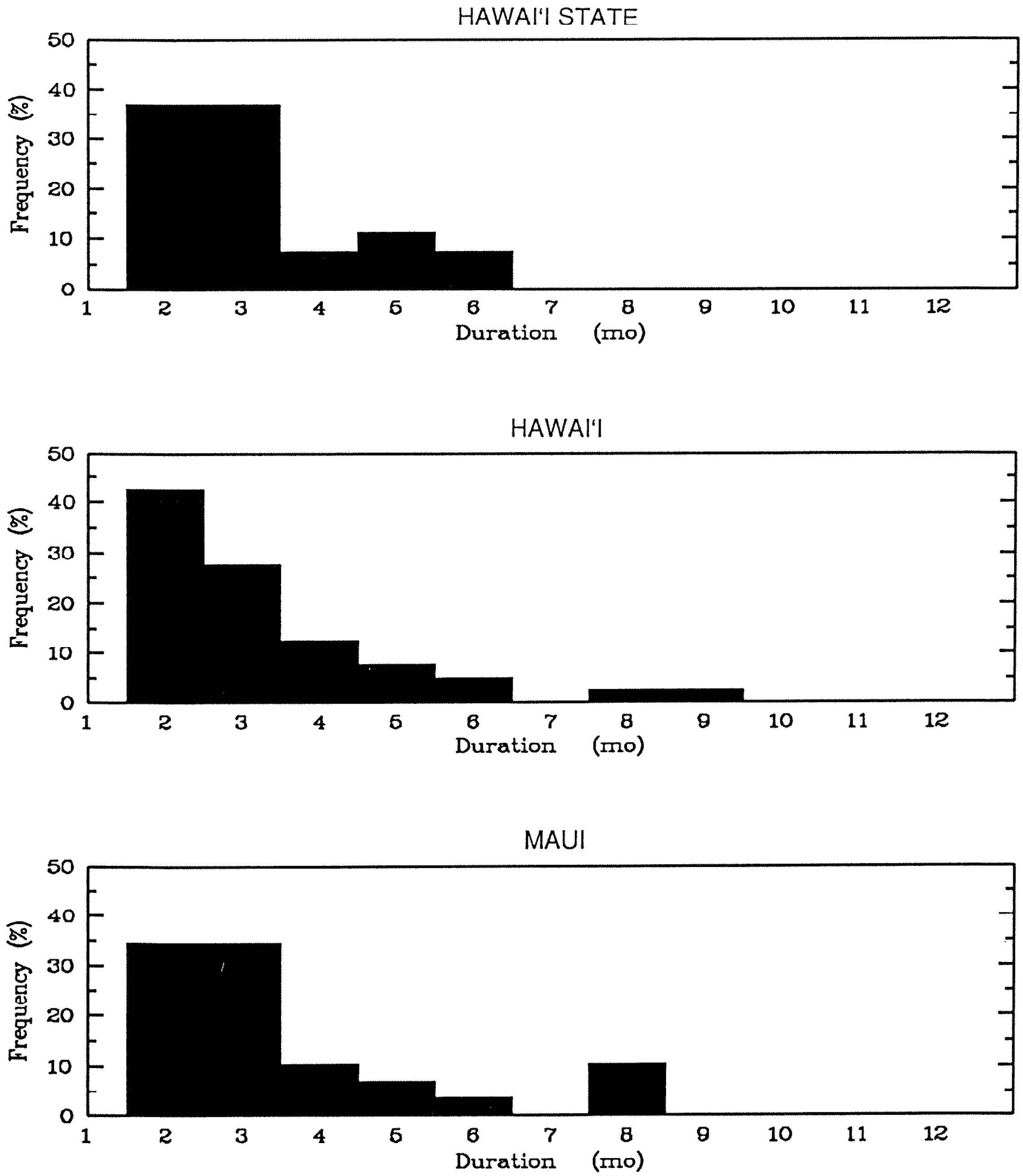


Figure 13. Drought duration frequency for Hawai'i State and six major islands

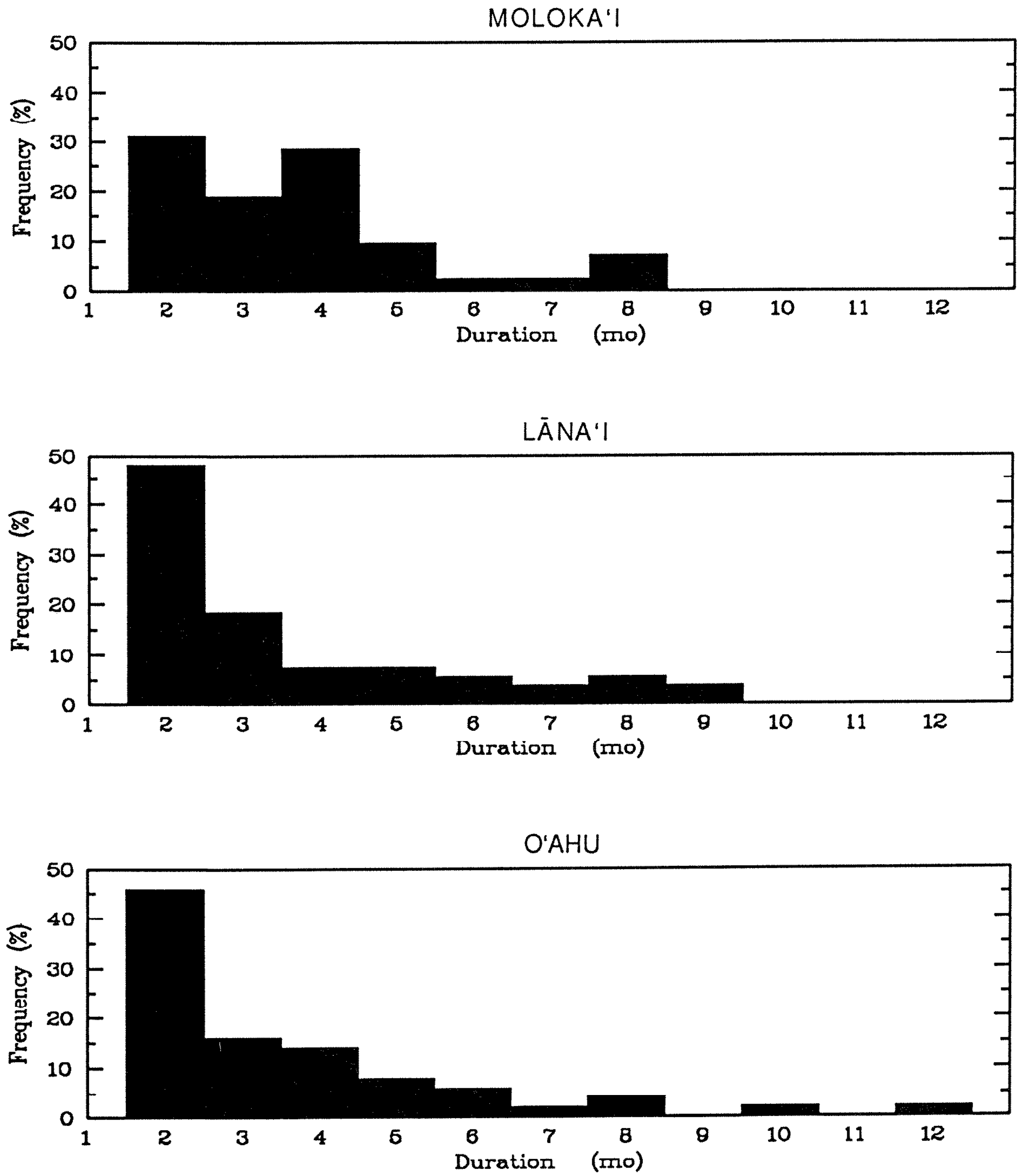


Figure 13.—*Continued*

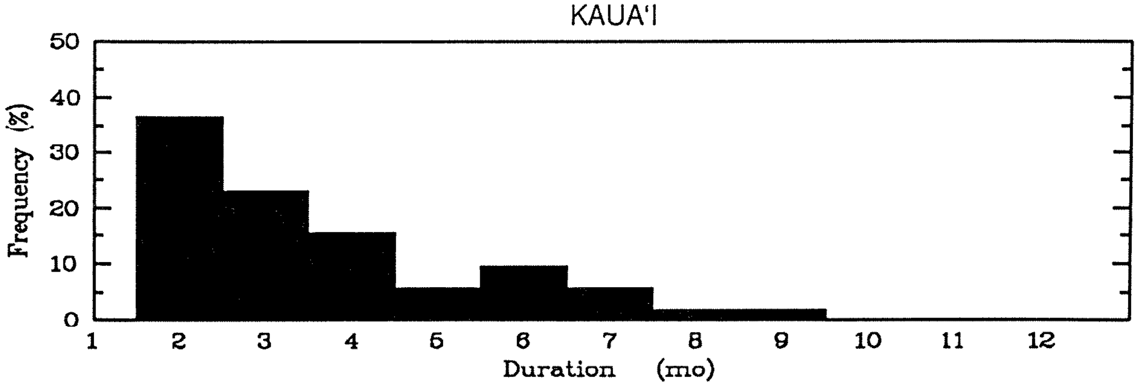


Figure 13.—*Continued*

Most droughts for individual islands and statewide droughts lasted 6 or fewer months. As expected, shorter droughts are the most numerous and frequency generally declines as duration increases.

The BMDI, based on departures from the mean monthly rainfall, does not reflect the normal annual cycle of rainfall found at most locations in Hawai'i. If this were not done, an index would tend to indicate drought during the dry season even when rainfall was near the mean for that time of year. The index would also miss important rainfall deficiencies occurring during the normally wet season. With this regular annual rainfall cycle removed, what, if any, are the tendencies for drought to begin or end in certain months? Figure 14 gives frequency histograms for month of drought onset for statewide and islandwide droughts. Statewide droughts begin most frequently in January, February, August, and November. Islandwide droughts begin most frequently between November and March, and occasionally between June and September. Droughts that begin in April, May, or October are relatively rare. Figure 15 shows the frequency histograms for month of drought termination. Statewide droughts end most frequently during periods of transition between winter storm and summer tradewind regimes, either in February, March, April, or May, when the tradewinds return, or in October, at the start of the traditionally recognized winter rainy season. Islandwide droughts are most likely to end during the January through March period and rarely end in June. Tables 13 and 14 gives the frequency of regional drought onset and termination by station. Highly variable from station to station, the onset of regional drought is more frequent between November and January and between April and July. Termination of drought is most likely in October or November or between January and April.

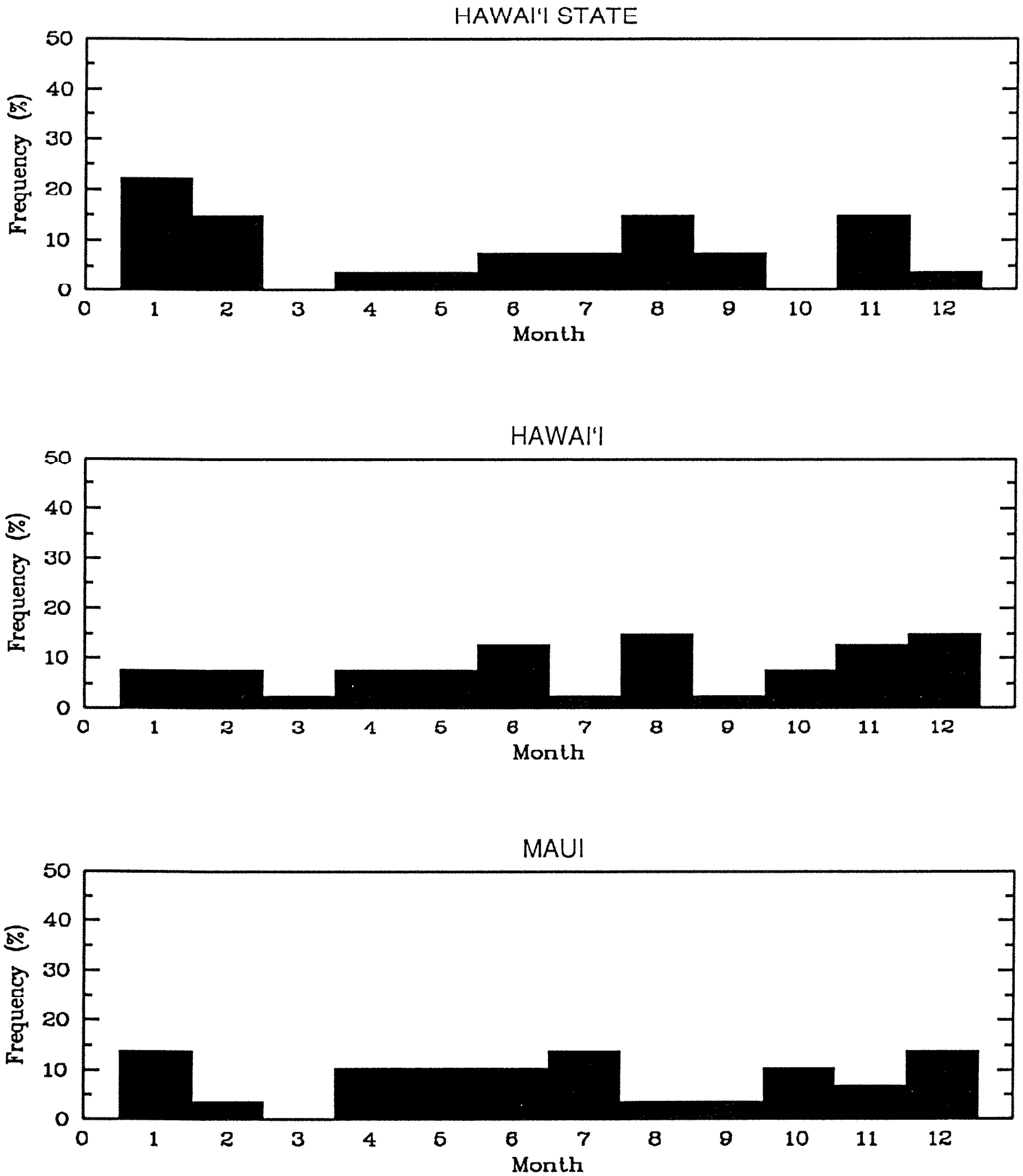


Figure 14. Frequency of drought onset by month for Hawai'i State and six major islands

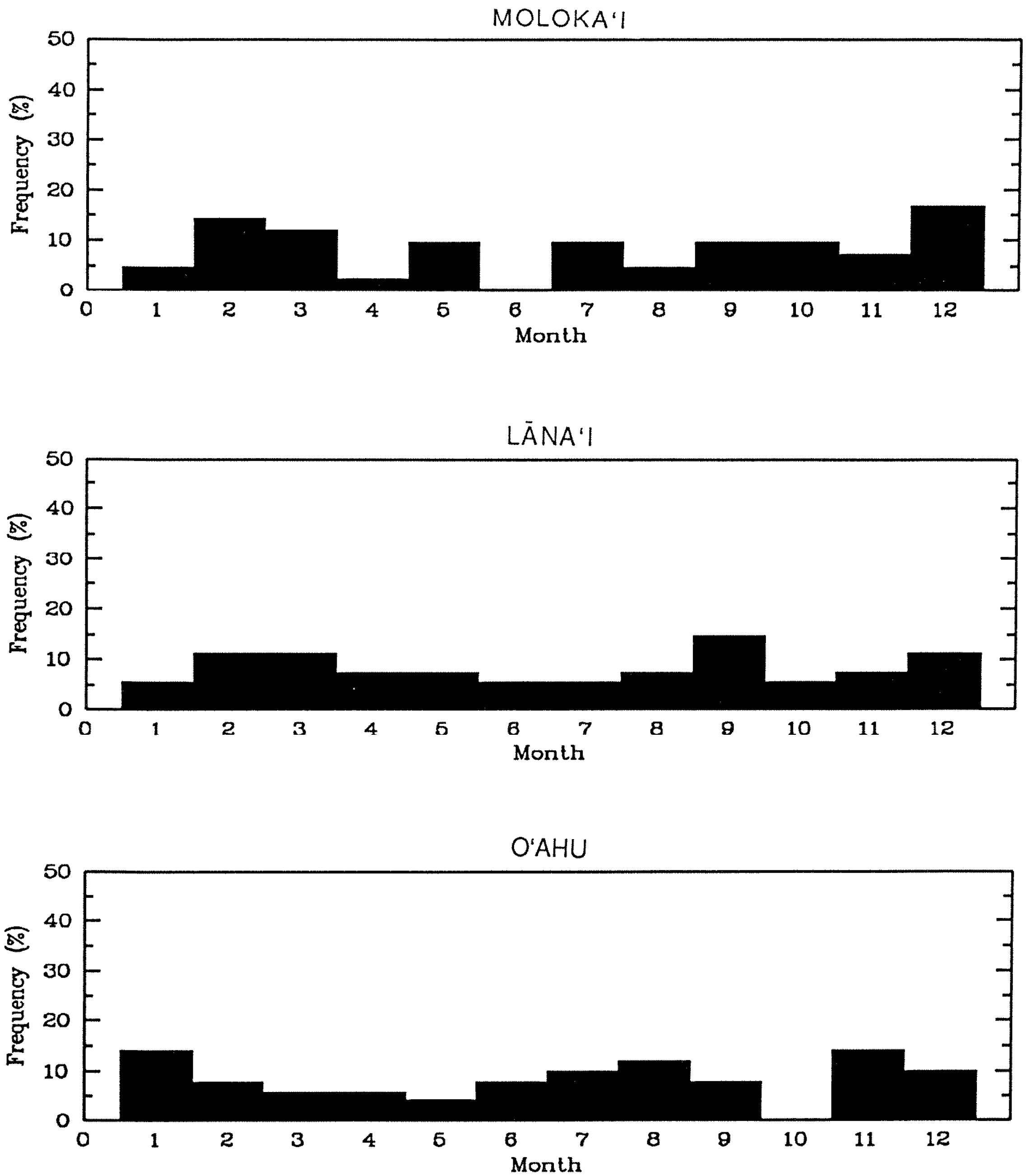


Figure 14.—*Continued*

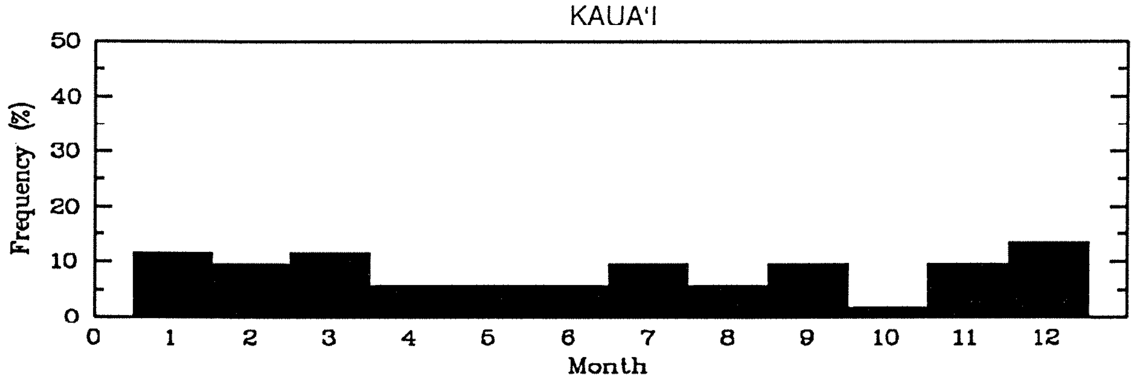


Figure 14.—*Continued*

Spatial Drought Characteristics

The spatial extent of dryness is an important element of our operational definition of drought for the state and for each island. Generally, the larger the area affected, the more serious are the impacts, and the fewer the alternatives for alleviating water shortages with regional water transfers. The importance of spatial extent is recognized and is the stimulus for analyzing drought on the basis of a DAI, such as the one presented earlier (Fig. 11 and App. Figs. D.13–D.15). In studying drought occurrence, questions arise concerning spatial characteristics other than just areal extent. For example, during statewide or islandwide drought events, some regions suffer worse than others. Are some regions inherently more drought-prone than others? If a distinct pattern of drought is evident on one island (for example, severe drought affecting only the windward areas), is that pattern likely to be seen simultaneously on other islands? Do droughts on islands close together tend to follow similar patterns as compared with more distant islands? When drought is affecting one region, is there a tendency for certain other regions to be similarly affected? We attempt to answer these questions in this section.

DROUGHT-PRONE REGIONS. Based on the list of 1,974 regional drought events, the long-term drought characteristics of each region were calculated (Table 15) The average magnitude of all events, the ratio of total drought months to the total months of record—drought months per month (DMPM), and the ratio of the number of droughts to the number of years of record—drought events per year (DEPY) are listed for each of the 48 stations in the network. A high negative number for average magnitude indicates that the region represented by the station is prone to intense droughts. The largest average magnitudes are for stations 65, 73.2, 92, 142, 175.1, 350, 442, 540, 782, 882, 1051, and 1115. With the exception of 73.2, the stations all have relatively high mean rainfall rates. One explanation for this is that larger negative

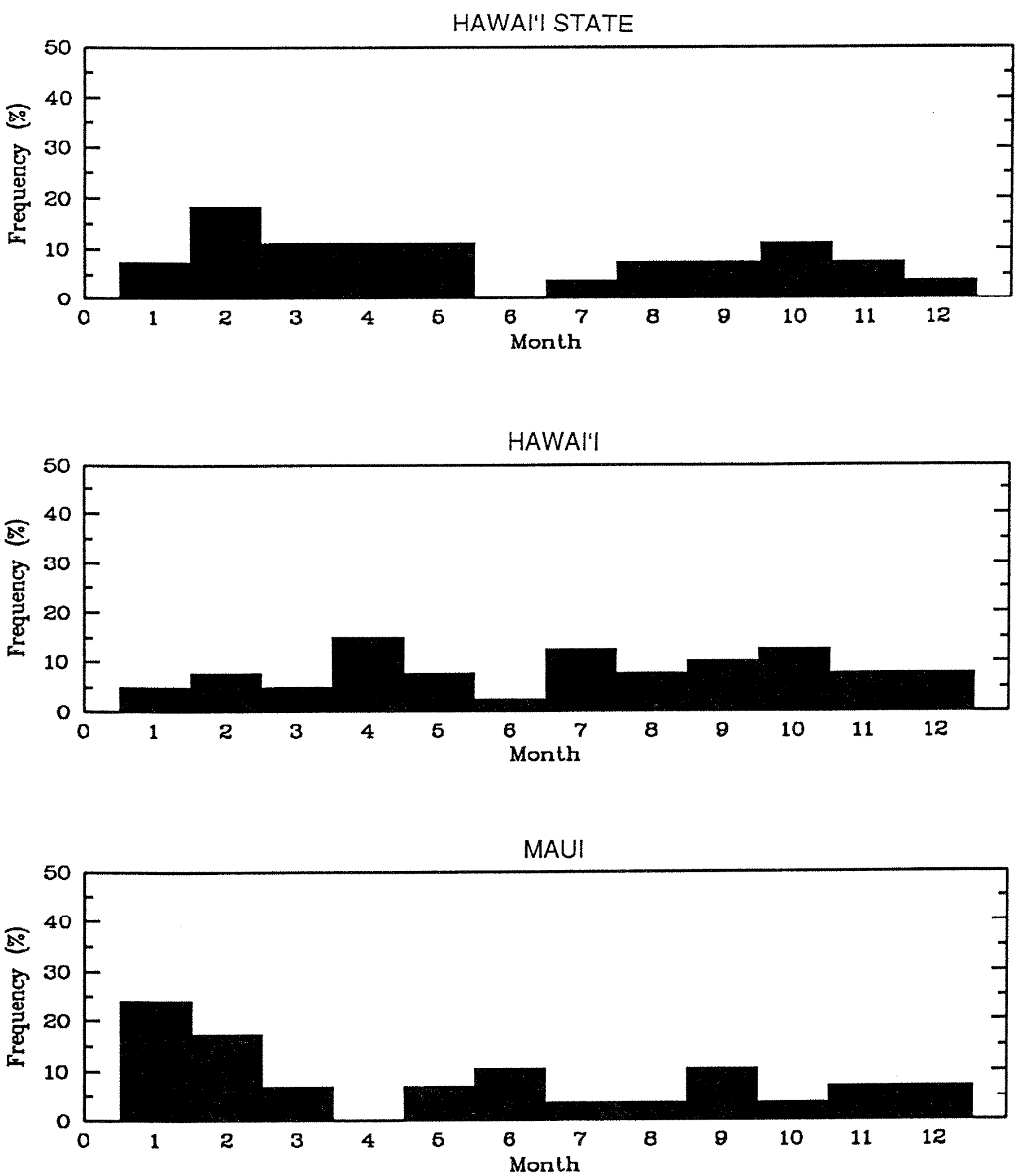


Figure 15. Frequency of drought termination by month for Hawai'i State and six major islands

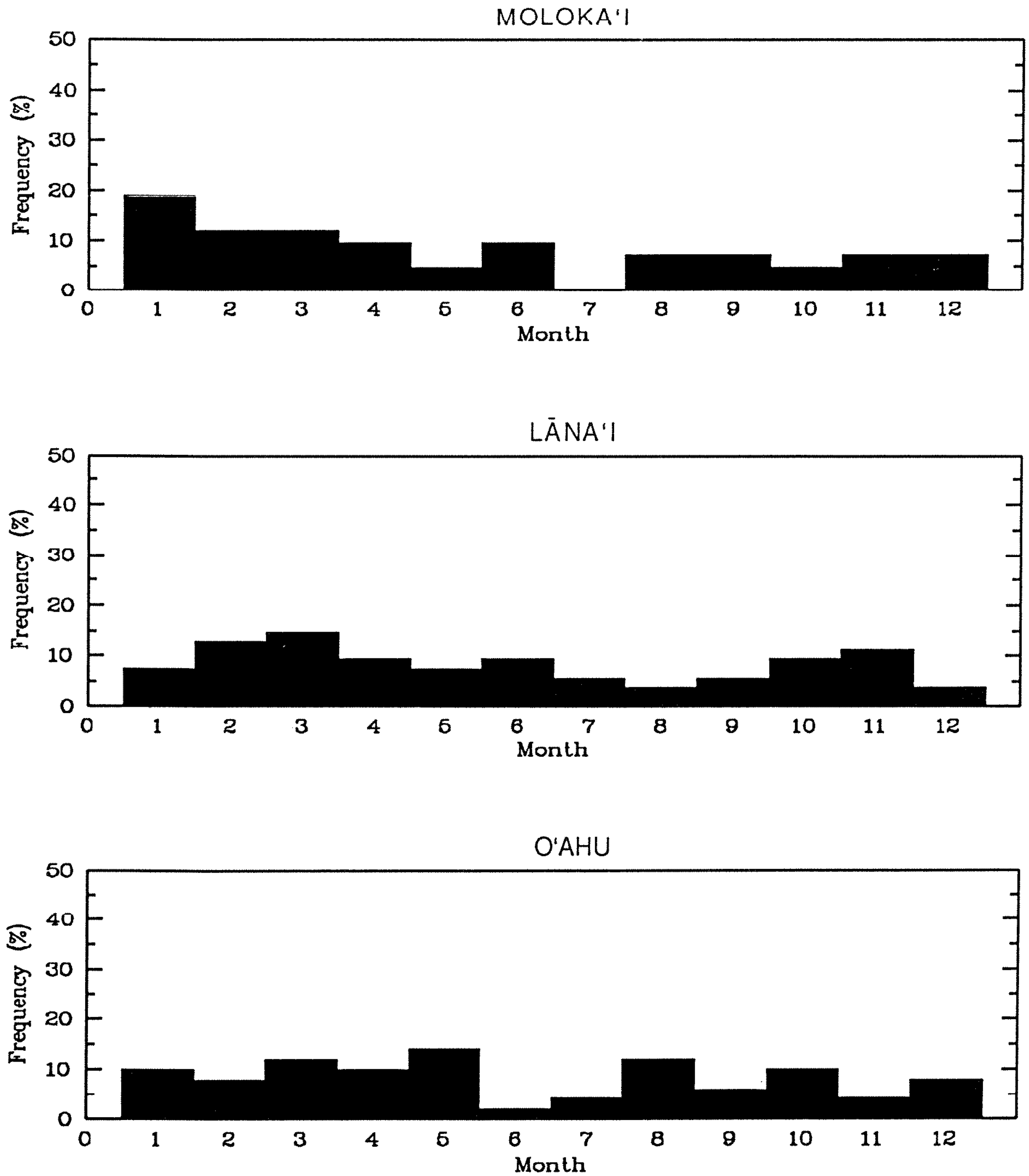


Figure 15.—*Continued*

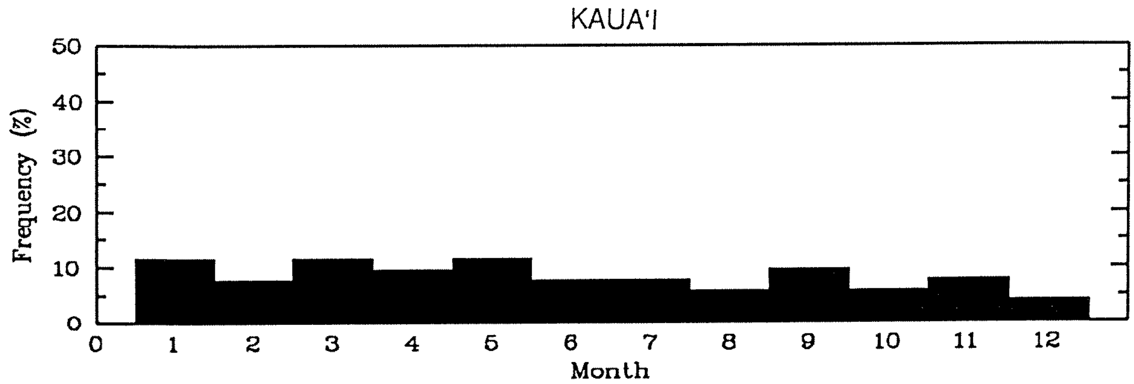


Figure 15.—*Continued*

departures are possible in wet areas than in dry areas. DMPM is a good indicator of proneness to drought. The values range from 0.11 to 0.24 with the highest being within, or leeward of, areas where rainfall maxima coincide with topographic peaks. By this measure, the most drought-prone regions in the state are South Kona, North Kohala, the higher elevations and southwestern slopes of Haleakalā, the peak area and leeward slopes of Pu'u Kukui, the peak and leeward side of East Moloka'i, central and southeastern Lāna'i , the summit and leeward slopes of the Ko'olau mountains, and the summit and northwestern slopes of Mt. Wai'ale'ale. A similar pattern holds for the DEPY statistic.

SPATIAL PATTERNS OF SEVERE DROUGHT. To examine the spatial patterns of drought, the approximate region represented by each station was delineated. Boundaries were constructed according to the proximity of other stations and according to topographical influences on rainfall. With these regional subdivisions, choropleth maps depicting drought severity could be produced.

Figures 16–18 show the three highest ranking statewide droughts. Darker shading indicates greater severity. The most severe statewide drought (Fig. 16), September 1977 to February 1978, was particularly intense in South Kona on Hawai'i and the Ko'olau mountains on O'ahu. Leeward areas of the southern islands (Hawai'i, Maui, Moloka'i, and Lāna'i) and the high rainfall areas of O'ahu and Kaua'i were generally hardest hit. During the May to October 1975 event (Fig. 17), drought was most severe on O'ahu and Kaua'i, particularly the Ko'olau mountains and Honolulu on O'ahu, and the northern coast, central, and Līhu'e areas of Kaua'i. The extreme western portions of each island tended to be less affected. The July to November 1953 drought (Fig. 18) was relatively uniformly distributed over the state.

Figure 19 shows that the December 1980 to July 1981 Hawai'i Island drought affected most severely the Hilo, Hāmākua, windward North Kohala, and Manukā areas. The 1971 and 1953 Hawai'i Island droughts (Figs. 20 and 21) were relatively evenly distributed over the

TABLE 13. FREQUENCY OF DROUGHT ONSET BY MONTH (%)

Station	J	F	M	A	M	J	J	A	S	O	N	D
2.00	25	7	4	7	7	7	4	11	7	14	4	4
14.00	21	7	0	4	11	4	18	0	4	7	11	14
21.00	7	11	7	4	14	4	7	7	7	7	18	7
54.00	14	0	4	18	0	14	14	4	4	11	11	7
65.00	4	7	11	7	4	4	18	14	0	11	4	18
73.20	7	7	7	11	7	4	4	14	14	11	0	14
92.00	0	0	7	11	11	14	11	7	0	14	14	11
92.10	18	14	7	0	11	14	4	4	14	0	7	7
103.00	11	0	11	7	11	21	0	7	11	4	11	7
118.00	11	4	0	14	7	4	11	4	7	18	7	14
142.00	0	0	0	7	14	21	11	7	4	4	21	1
147.00	7	7	18	0	14	11	4	4	18	7	7	4
175.10	14	0	4	18	29	4	7	7	0	7	4	7
194.00	14	0	0	36	11	4	7	0	11	4	7	7
217.00	11	4	4	21	11	14	7	7	0	7	11	4
250.00	7	7	4	11	14	11	11	4	14	0	11	7
256.00	14	4	14	7	0	0	18	0	4	7	11	21
310.00	11	11	21	0	0	0	0	0	18	14	7	18
333.00	21	0	0	18	14	14	0	4	11	4	14	0
350.00	7	0	0	11	14	14	18	0	4	7	14	11
354.00	14	11	11	11	0	11	7	4	0	7	14	11
374.00	14	4	7	7	11	7	11	0	7	18	7	7
406.00	11	4	7	11	18	11	7	7	4	4	7	11
442.00	7	0	7	14	0	18	21	4	4	11	7	7
483.00	0	7	4	7	11	32	4	0	7	11	7	11
511.00	11	11	4	7	14	4	11	7	11	0	7	14
529.00	14	7	4	4	11	4	11	7	21	0	7	11
540.00	14	7	7	14	14	7	11	7	7	0	7	4
562.00	7	7	7	7	11	7	11	11	14	0	4	14
650.00	14	11	0	11	7	14	4	7	14	4	7	7
684.00	7	4	14	4	4	14	18	14	4	4	0	14
690.00	11	14	4	14	7	7	0	11	7	4	4	18
707.00	14	7	0	4	11	11	7	11	7	7	11	11
741.00	7	14	7	7	18	7	11	4	11	7	7	0
782.00	4	7	7	18	18	11	11	4	4	4	7	7
794.00	0	7	11	0	7	4	25	7	7	14	7	11
798.00	14	14	4	4	11	4	4	4	18	4	14	7
847.00	7	14	11	7	11	4	11	14	4	0	11	7
863.00	18	11	0	0	14	7	11	11	7	4	11	7
883.00	7	4	4	7	25	11	11	4	7	0	7	14
912.00	18	7	14	4	4	14	7	0	0	7	14	11
965.00	18	7	7	0	4	0	29	4	7	14	0	11
1020.00	18	4	7	7	7	0	4	11	7	11	11	14
1026.00	11	14	0	14	0	7	7	4	14	11	11	7
1051.00	11	11	7	14	4	7	7	11	0	11	7	11
1110.00	21	7	7	4	11	7	4	4	4	14	7	11
1115.00	7	7	7	14	14	7	14	7	4	11	7	0
1134.00	11	14	0	0	18	7	7	11	7	7	4	14
TOTAL	534	326	292	427	489	427	460	295	360	347	408	455

TABLE 14. FREQUENCY OF DROUGHT TERMINATION BY MONTH (%)

Station	J	F	M	A	M	J	J	A	S	O	N	D
2.00	4	7	4	4	7	7	4	11	4	18	29	4
14.00	7	11	11	25	7	7	4	7	4	11	7	0
21.00	14	4	11	14	7	7	4	7	7	11	11	4
54.00	7	7	14	11	0	7	14	11	11	4	7	7
65.00	7	4	11	11	7	7	18	4	11	7	7	7
73.20	4	14	7	0	7	11	11	0	21	14	7	4
92.00	11	4	7	18	4	11	14	11	4	14	4	0
92.10	7	14	7	14	11	7	14	0	0	7	14	4
103.00	14	4	14	4	11	0	7	11	7	11	7	11
118.00	11	14	14	11	11	0	4	7	4	11	0	14
142.00	4	7	7	11	0	4	11	11	18	18	7	4
147.00	0	7	7	4	7	18	11	4	7	11	11	14
175.10	7	4	4	18	0	4	11	11	7	14	11	11
194.00	7	18	7	4	11	11	7	7	14	11	4	0
217.00	18	4	11	7	4	11	7	11	11	11	7	0
250.00	11	7	11	4	7	7	4	7	0	14	21	7
256.00	11	11	18	7	4	7	7	7	7	4	11	7
310.00	11	25	14	11	29	0	0	0	0	0	4	7
333.00	11	11	21	0	0	7	4	18	7	11	0	11
350.00	11	14	4	7	0	7	18	7	18	7	0	7
354.00	11	21	7	14	4	4	4	11	7	7	11	0
374.00	14	7	4	11	7	7	14	4	4	7	11	11
406.00	11	18	4	11	4	4	11	7	11	11	7	4
442.00	14	7	4	4	7	0	11	7	7	21	7	11
483.00	18	7	18	0	14	4	4	4	7	14	0	11
511.00	11	7	14	4	11	7	7	0	7	11	11	11
529.00	14	11	14	7	0	4	4	11	14	7	4	11
540.00	0	11	14	18	7	0	7	7	14	4	11	7
562.00	18	14	4	11	4	7	11	11	4	4	4	11
650.00	4	21	14	0	14	4	4	4	7	11	11	7
684.00	11	14	14	11	14	4	0	4	11	4	4	11
690.00	11	4	29	0	14	4	7	7	4	4	11	7
707.00	18	7	11	18	4	4	4	11	7	7	4	7
741.00	7	0	18	4	14	14	7	0	11	11	11	4
782.00	14	11	14	4	11	4	0	4	11	18	0	11
794.00	18	7	11	7	11	4	0	4	14	11	7	7
798.00	14	7	18	7	7	11	4	4	7	7	14	0
847.00	14	14	7	4	7	4	11	0	11	14	11	4
863.00	7	11	14	11	14	4	0	4	11	4	14	7
883.00	7	7	4	7	11	7	4	14	7	14	11	7
912.00	7	4	21	7	14	7	7	11	4	4	7	7
965.00	0	11	7	21	7	7	0	4	14	7	14	7
1020.00	11	4	21	11	4	7	7	4	7	4	14	7
1026.00	7	7	11	4	7	11	7	7	7	11	18	4
1051.00	4	21	0	4	14	18	7	0	7	4	11	11
1110.00	7	7	18	11	4	7	11	11	7	4	7	7
1115.00	14	11	11	7	4	7	11	7	4	11	4	11
1134.00	4	7	18	4	14	7	7	11	4	7	7	11
TOTAL	467	469	548	407	381	312	345	325	392	452	415	337

TABLE 15. AVERAGE MAGNITUDE, DROUGHT MONTHS PER MONTH (DMPM), DROUGHT EVENTS PER YEAR (DEPY)

Station	Avg Mag	DMPM	DEPY
2.00	-3.08	0.24	0.48
14.00	-2.92	0.12	0.29
21.00	-2.64	0.13	0.27
54.00	-2.96	0.12	0.28
65.00	-3.26	0.12	0.29
73.20	-3.23	0.11	0.33
92.00	-3.30	0.12	0.26
92.10	-3.10	0.16	0.33
103.00	-2.91	0.15	0.36
118.00	-2.73	0.13	0.27
142.00	-3.26	0.13	0.26
147.00	-2.44	0.21	0.50
175.10	-3.24	0.13	0.27
194.00	-3.01	0.16	0.33
217.00	-3.00	0.15	0.27
250.00	-2.82	0.15	0.34
256.00	-2.76	0.13	0.42
310.00	-2.62	0.11	0.33
333.00	-2.79	0.15	0.34
350.00	-3.26	0.14	0.34
354.00	-2.94	0.14	0.31
374.00	-3.13	0.21	0.36
406.00	-3.04	0.12	0.27
442.00	-3.25	0.13	0.31
483.00	-2.87	0.14	0.27
511.00	-2.97	0.12	0.32
529.00	-2.70	0.14	0.32
540.00	-3.30	0.21	0.49
562.00	-3.07	0.12	0.32
650.00	-2.86	0.14	0.29
684.00	-2.96	0.19	0.44
690.00	-2.74	0.13	0.29
707.00	-3.11	0.12	0.27
741.00	-2.58	0.13	0.25
782.00	-3.50	0.18	0.29
794.00	-2.79	0.11	0.25
798.00	-2.65	0.10	0.25
847.00	-2.81	0.12	0.27
863.00	-3.05	0.15	0.32
883.00	-3.44	0.20	0.40
912.00	-2.86	0.13	0.27
965.00	-2.61	0.13	0.29
1020.00	-2.95	0.11	0.27
1026.00	-2.63	0.12	0.29
1051.00	-3.43	0.15	0.33
1110.00	-2.92	0.12	0.27
1115.00	-3.21	0.16	0.35
1134.00	-3.15	0.13	0.28

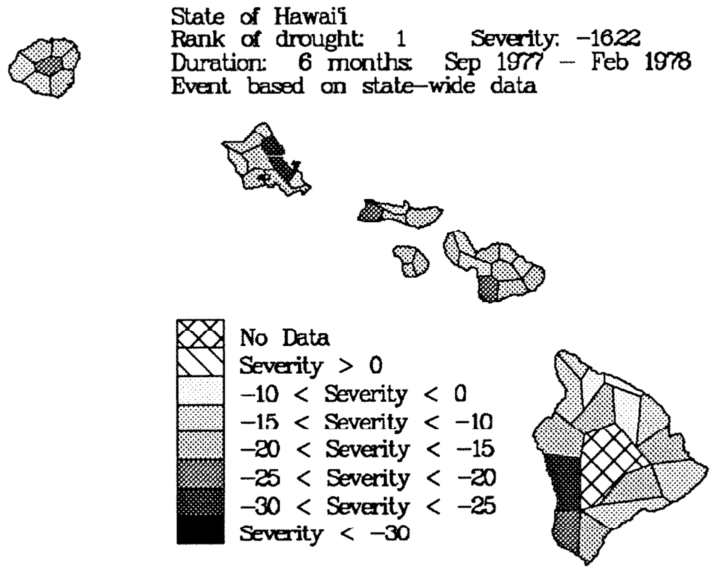


Figure 16. Drought severity, rank 1, statewide

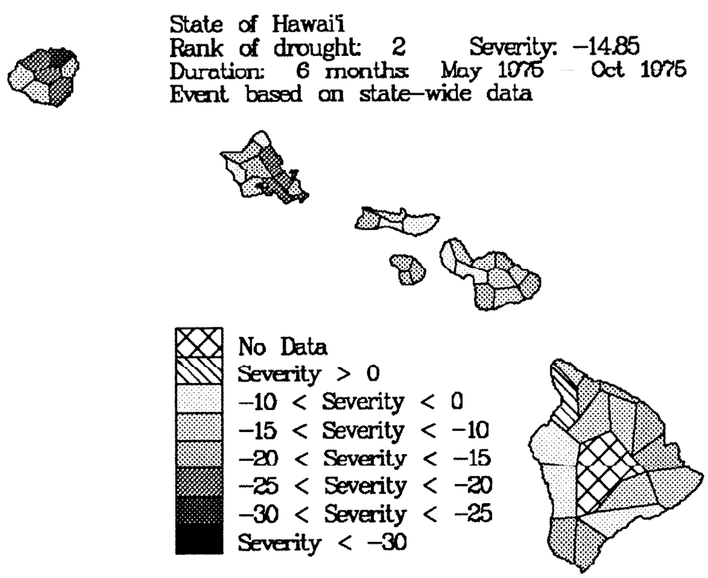


Figure 17. Drought severity, rank 2, statewide

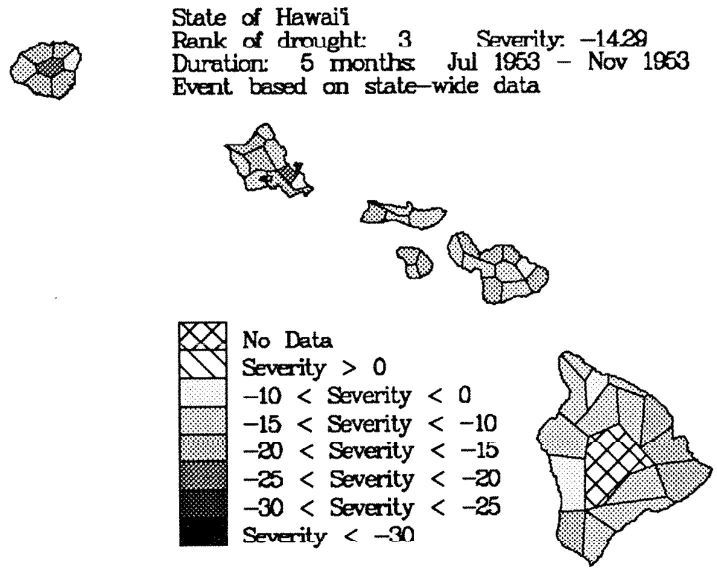


Figure 18. Drought severity, rank 3, statewide

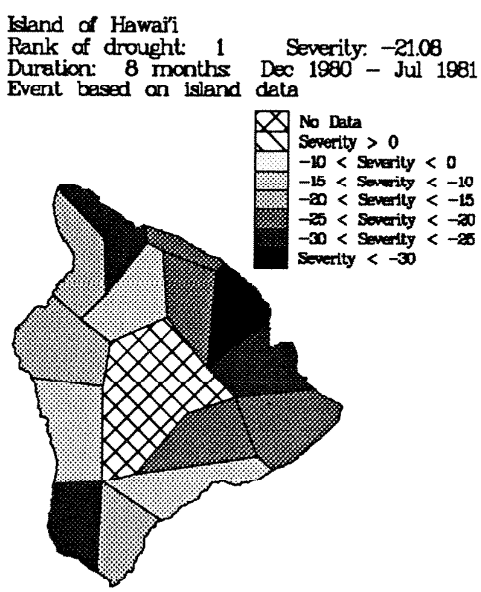


Figure 19. Drought severity, rank 1, Hawai'i Island

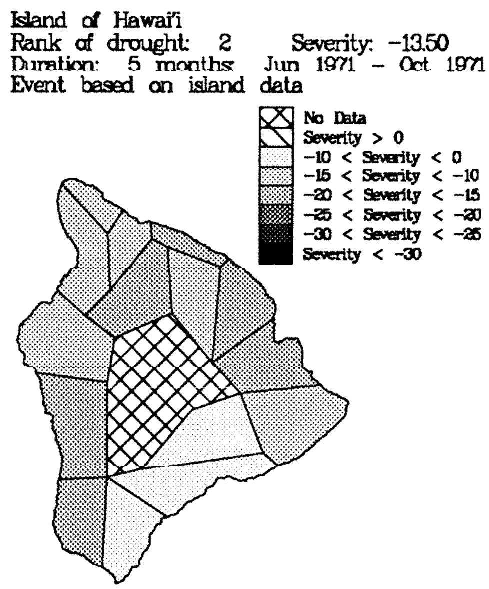


Figure 20. Drought severity, rank 2, Hawai'i Island

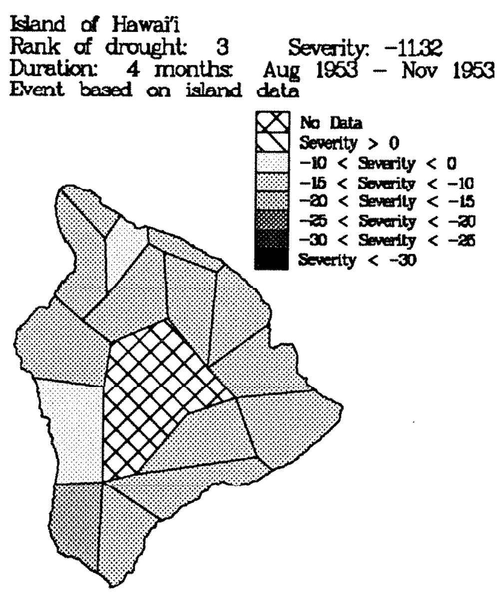


Figure 21. Drought severity, rank 3, Hawai'i Island

island. In the three Maui droughts shown in Figures 22–24, severity tended to be greatest on the northern and eastern Haleakalā slopes and the northern and western Pu'u Kukui slopes. The most severe droughts on Moloka'i and Lāna'i (Figs. 25–27 and 28–30) each exhibited different spatial patterns. The November 1983 to October 1984, April 1953 to January 1954, and August 1977 to March 1978 O'ahu droughts (Figs. 31–33) tended to be most severe in the Ko'olau mountain range, Schofield, and Honolulu areas. On Kaua'i (Figs. 34–36), the most severe droughts affected the Wai'ale'ale, Hanalei, and Līhu'e areas.

INTERREGIONAL CORRELATION. The preceding examination of spatial drought distribution suggests that nearby islands exhibit similar spatial patterns during droughts and that certain within-island patterns tend to recur. To gain a complete picture of the spatial relationships for rainfall variability, the monthly BMDI index for each station was correlated against that of each other station. The results are given in Table 16.

Interstation correlation coefficients are highest for stations in close proximity and for those with similar locations relative to topographic barriers. For example, Station 2 is located on the southwest slope of Mauna Loa, Hawai'i Island (Fig. 2). Station 73.2, with a similar exposure and elevation, is the station that has the highest correlation with Station 2. Stations 14 and 21, although closer, have lower correlations with Station 2 because of their southeast aspect. Correlation with Station 2 generally decreases toward the northwest for stations on other islands. Note that Station 250 on Maui has a relatively high correlation with Station 2 and has a similar exposure. Another good example is Station 142, located near the coast on the northeastern Mauna Kea slope of Hawai'i Island. It is highly correlated with other nearby windward stations, such as Stations 65, 92, and 217. It is also well correlated with windward stations on other islands, such as Stations 350 and 442 on Maui, 782 and 882 on O'ahu, and 1115 on Kaua'i. Not surprisingly, these figures indicate a tendency for droughts to affect simultaneously areas in close proximity and areas with similar topographic exposures.

Persistence of Low Rainfall

Hawai'i often experiences multi-year periods of above- or below-normal annual rainfall. This is commonly interpreted as an indication of long-term persistence, perhaps associated with large-scale periodic or nonperiodic atmospheric circulation features. We tested the annual rainfall record of two stations on O'ahu for evidence of persistence by first identifying runs of consecutive years below the median. Ten different random number series of the same length as the rainfall record were generated by computer. Runs of below median values were identified in each random number series. Table 17 shows that, while the longest run of consecutive years with below median annual rainfall at Station 741 was 8 years, the run-length frequencies

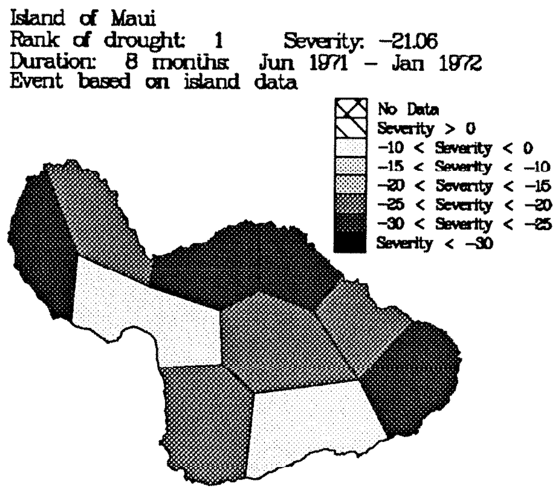


Figure 22. Drought severity, rank 1, Maui Island

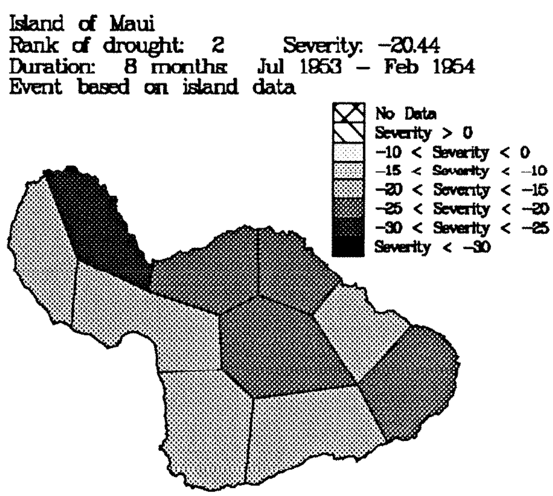


Figure 23. Drought severity, rank 2, Maui Island

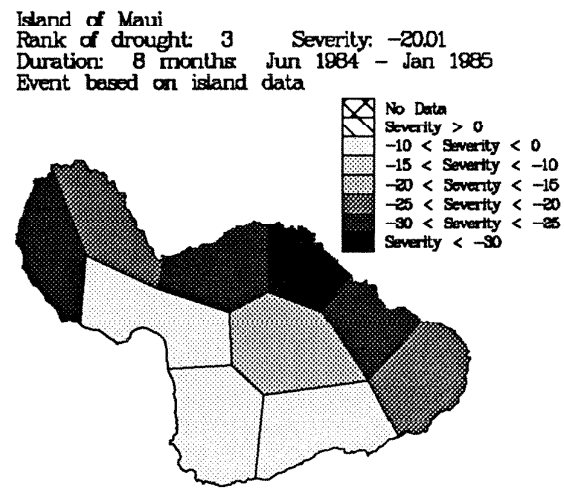


Figure 24. Drought severity, rank 3, Maui Island

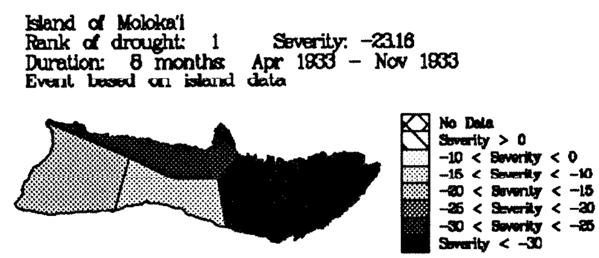


Figure 25. Drought severity, rank 1, Moloka'i Island

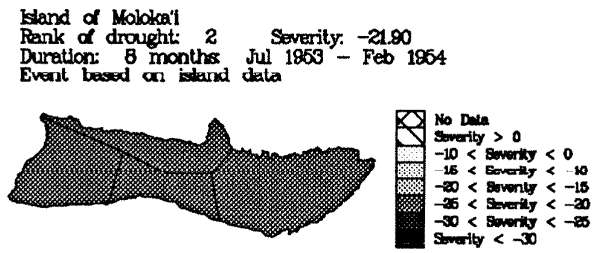


Figure 26. Drought severity, rank 2, Moloka'i Island

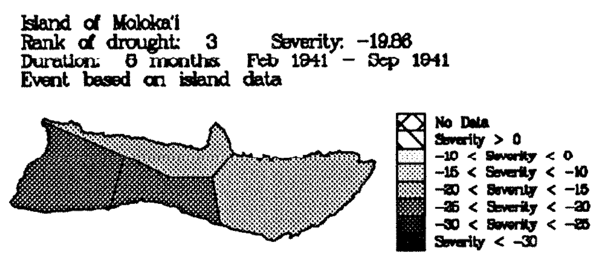


Figure 27. Drought severity, rank 3, Moloka'i Island

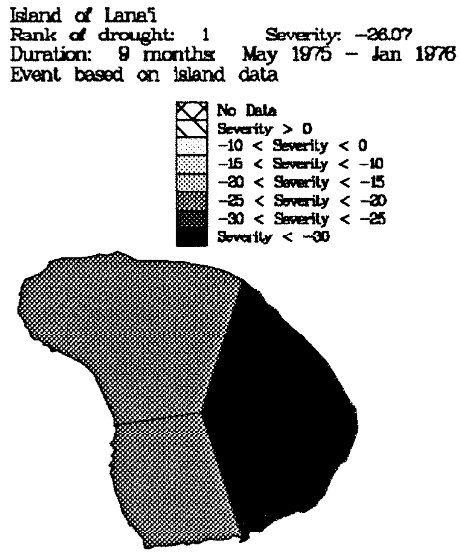


Figure 28. Drought severity, rank 1, Lāna'i Island

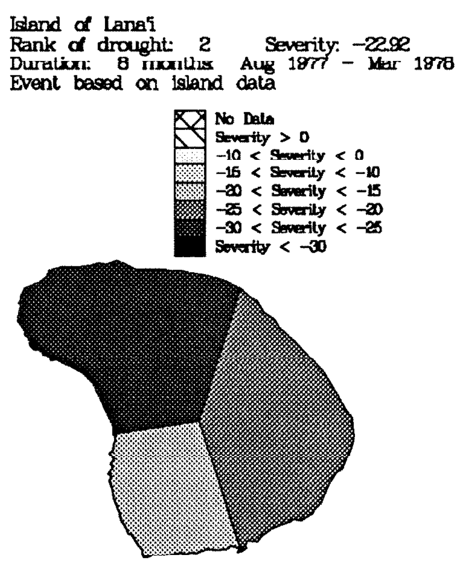


Figure 29. Drought severity, rank 2, Lāna'i Island

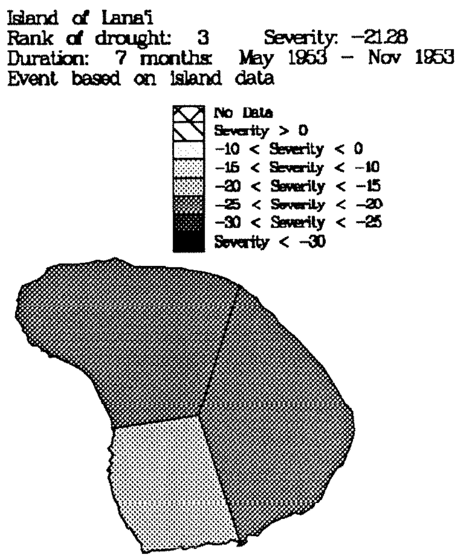


Figure 30. Drought severity, rank 3, Lāna'i Island

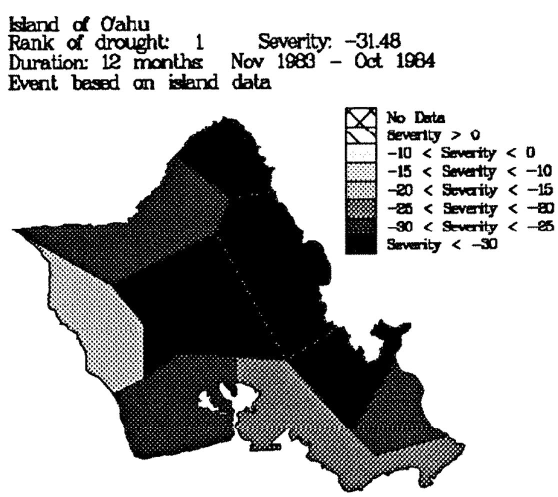


Figure 31. Drought severity, rank 1, O'ahu Island

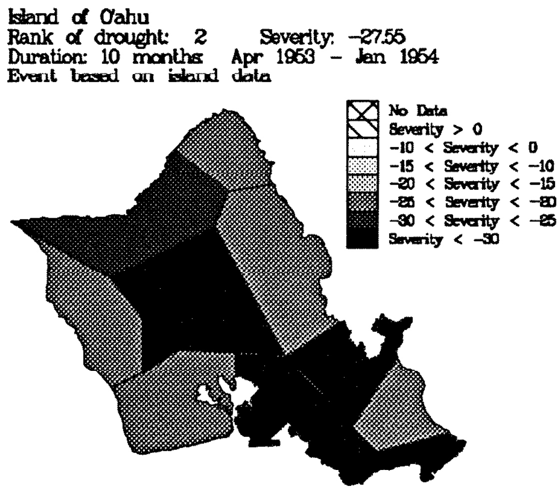


Figure 32. Drought severity, rank 2, O‘ahu Island

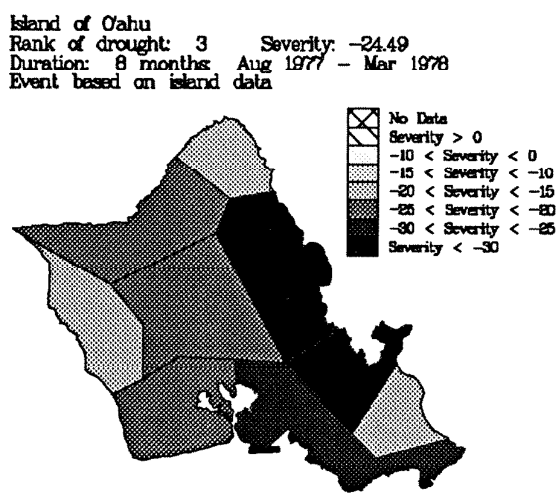


Figure 33. Drought severity, rank 3, O‘ahu Island

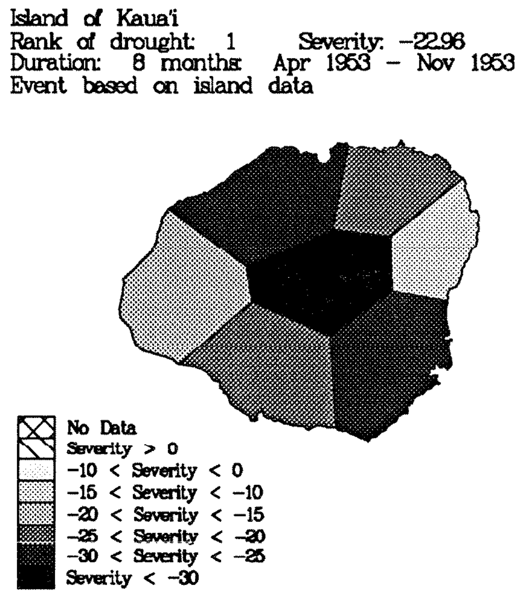


Figure 34. Drought severity, rank 1, Kaua'i Island

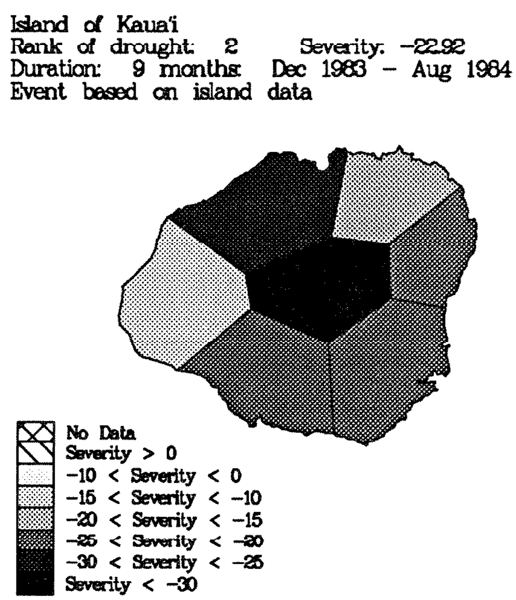


Figure 35. Drought severity, rank 2, Kaua'i Island

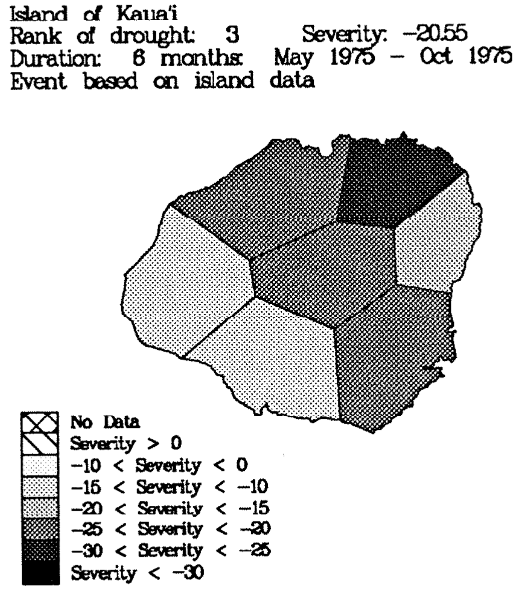


Figure 36. Drought severity, rank 3, Kaua'i Island

are indistinguishable from those of random number series. A similar conclusion can be made for Station 782 (Table 18). We conclude that annual rainfall does not exhibit persistence in Hawai'i. This suggests that meteorological fluctuations of multi-year scales are not strongly indicated.

Monthly rainfall is more likely to be persistent because of the time-scale of atmospheric circulation changes, such as ENSO, that influence rainfall. The monthly rainfall records of Stations 741 and 782 were analyzed by identifying runs of consecutive-month periods below the median. The individual monthly medians were used to determine the dry periods. The run-length frequencies were again compared with those computed from random number series. In Table 19, we can see that short-run lengths (1 or 2 mo) at Station 741 are significantly less frequent than for random series. Six-month runs are more frequent than random. For Station 782, shown in Table 20, 1- and 2-month runs are less frequent than random, and runs of 9 to 12 months are somewhat more frequent. These comparisons indicate some tendency for persistence in monthly rainfall for both dry (741) and wet (782) stations. The most significant deviations from random are in the shorter runs, suggesting a first-order Markov process.

Conditional Drought Probabilities

The evidence presented suggests that there is some persistence in monthly rainfall in Hawai'i. This leads us to consider that some predictive value may be found in the statistics of drought

TABLE 16. CROSS-CORRELATION OF MONTHLY BMDI FOR NETWORK STATIONS

STATION	STATION							
	2	14	21	54	65	73.2	92	92.1
2	1.00	0.44	0.39	0.39	0.38	0.55	0.38	0.45
14	0.44	1.00	0.85	0.66	0.55	0.31	0.52	0.41
21	0.39	0.85	1.00	0.59	0.52	0.28	0.47	0.42
54	0.39	0.66	0.59	1.00	0.73	0.21	0.77	0.28
65	0.38	0.55	0.52	0.73	1.00	0.19	0.85	0.26
73.2	0.55	0.31	0.28	0.21	0.19	1.00	0.19	0.63
92	0.38	0.52	0.47	0.77	0.85	0.19	1.00	0.22
92.1	0.45	0.41	0.42	0.28	0.26	0.63	0.22	1.00
103	0.43	0.40	0.41	0.45	0.46	0.24	0.46	0.32
118	0.25	0.33	0.31	0.53	0.56	0.03	0.59	0.07
142	0.39	0.48	0.42	0.72	0.80	0.16	0.90	0.15
147	0.25	0.34	0.38	0.28	0.25	0.32	0.18	0.45
175.1	0.28	0.31	0.26	0.54	0.58	0.14	0.61	0.20
194	0.27	0.18	0.15	0.42	0.46	0.02	0.51	0.03
217	0.24	0.30	0.26	0.53	0.59	0.04	0.63	0.08
250	0.44	0.41	0.46	0.27	0.29	0.45	0.21	0.52
256	0.33	0.50	0.53	0.41	0.40	0.35	0.34	0.43
310	0.31	0.36	0.41	0.24	0.23	0.27	0.20	0.40
333	0.31	0.33	0.31	0.50	0.54	0.17	0.56	0.19
350	0.33	0.33	0.28	0.58	0.68	0.13	0.72	0.13
354	0.41	0.36	0.36	0.41	0.52	0.25	0.49	0.27
374	0.37	0.26	0.22	0.43	0.42	0.23	0.47	0.23
406	0.42	0.28	0.27	0.40	0.46	0.24	0.48	0.23
442	0.34	0.29	0.23	0.51	0.61	0.14	0.64	0.13
483	0.33	0.38	0.42	0.38	0.41	0.22	0.38	0.32
511	0.36	0.41	0.43	0.27	0.24	0.37	0.19	0.47
529	0.28	0.41	0.48	0.32	0.26	0.29	0.22	0.39
540	0.20	0.19	0.24	0.30	0.31	0.09	0.28	0.16
562	0.27	0.31	0.34	0.29	0.32	0.27	0.29	0.30
650	0.32	0.36	0.41	0.22	0.18	0.36	0.13	0.48
684	0.37	0.38	0.41	0.28	0.29	0.34	0.23	0.43
690	0.24	0.36	0.44	0.25	0.18	0.30	0.15	0.42
707	0.39	0.44	0.45	0.39	0.40	0.36	0.37	0.37
741	0.30	0.44	0.49	0.30	0.28	0.36	0.24	0.45
782	0.37	0.41	0.37	0.52	0.60	0.25	0.61	0.27
794	0.27	0.46	0.54	0.32	0.32	0.27	0.27	0.39
798	0.27	0.47	0.52	0.27	0.23	0.31	0.19	0.43
847	0.34	0.48	0.52	0.33	0.34	0.33	0.27	0.40
863	0.41	0.48	0.50	0.39	0.33	0.37	0.31	0.43
883	0.37	0.38	0.35	0.48	0.58	0.28	0.60	0.26
912	0.37	0.46	0.50	0.32	0.38	0.34	0.31	0.39
965	0.24	0.43	0.43	0.25	0.21	0.26	0.18	0.34
1020	0.32	0.45	0.46	0.33	0.38	0.29	0.32	0.33
1026	0.23	0.39	0.40	0.23	0.18	0.33	0.13	0.38
1051	0.39	0.44	0.41	0.52	0.56	0.29	0.52	0.26
1110	0.29	0.43	0.47	0.35	0.39	0.25	0.32	0.30
1115	0.38	0.34	0.30	0.49	0.54	0.20	0.54	0.21
1134	0.32	0.42	0.42	0.39	0.43	0.29	0.40	0.29

TABLE 16.—*Continued*

STATION	STATION							
	103	118	142	147	175.1	194	217	250
2	0.43	0.25	0.39	0.25	0.28	0.27	0.24	0.44
14	0.40	0.33	0.48	0.34	0.31	0.18	0.30	0.41
21	0.41	0.31	0.42	0.38	0.26	0.15	0.26	0.46
54	0.45	0.53	0.72	0.28	0.54	0.42	0.53	0.27
65	0.46	0.56	0.80	0.25	0.58	0.46	0.59	0.29
73.2	0.24	0.03	0.16	0.32	0.14	0.02	0.04	0.45
92	0.46	0.59	0.90	0.18	0.61	0.51	0.63	0.21
92.1	0.32	0.07	0.15	0.45	0.20	0.03	0.08	0.52
103	1.00	0.67	0.48	0.35	0.58	0.66	0.60	0.33
118	0.67	1.00	0.66	0.16	0.71	0.80	0.87	0.15
142	0.48	0.66	1.00	0.19	0.68	0.60	0.72	0.22
147	0.35	0.16	0.19	1.00	0.26	0.12	0.18	0.44
175.1	0.58	0.71	0.68	0.26	1.00	0.76	0.80	0.16
194	0.66	0.80	0.60	0.12	0.76	1.00	0.81	0.07
217	0.60	0.87	0.72	0.18	0.80	0.81	1.00	0.15
250	0.33	0.15	0.22	0.44	0.16	0.07	0.15	1.00
256	0.31	0.13	0.31	0.41	0.20	0.05	0.12	0.59
310	0.42	0.24	0.19	0.34	0.30	0.18	0.24	0.56
333	0.56	0.67	0.58	0.24	0.56	0.58	0.61	0.30
350	0.49	0.66	0.78	0.14	0.71	0.67	0.74	0.22
354	0.44	0.47	0.56	0.30	0.50	0.44	0.54	0.43
374	0.34	0.40	0.45	0.14	0.44	0.32	0.38	0.26
406	0.53	0.56	0.53	0.24	0.62	0.58	0.60	0.38
442	0.50	0.68	0.70	0.10	0.71	0.68	0.73	0.18
483	0.52	0.50	0.43	0.38	0.53	0.42	0.53	0.51
511	0.35	0.19	0.19	0.38	0.23	0.13	0.19	0.58
529	0.40	0.26	0.23	0.42	0.29	0.18	0.25	0.52
540	0.37	0.35	0.33	0.26	0.38	0.31	0.38	0.33
562	0.46	0.39	0.32	0.29	0.46	0.37	0.41	0.43
650	0.28	0.06	0.10	0.40	0.11	0.01	0.06	0.58
684	0.35	0.21	0.25	0.43	0.23	0.14	0.24	0.57
690	0.31	0.12	0.12	0.38	0.18	0.08	0.14	0.53
707	0.32	0.24	0.33	0.24	0.29	0.18	0.25	0.41
741	0.26	0.18	0.20	0.33	0.20	0.05	0.16	0.51
782	0.41	0.45	0.61	0.16	0.50	0.45	0.49	0.36
794	0.31	0.23	0.24	0.31	0.25	0.09	0.23	0.47
798	0.24	0.14	0.15	0.25	0.13	0.02	0.12	0.47
847	0.34	0.23	0.25	0.32	0.24	0.13	0.22	0.49
863	0.34	0.12	0.25	0.27	0.20	0.08	0.11	0.49
883	0.39	0.40	0.58	0.21	0.49	0.40	0.44	0.33
912	0.30	0.20	0.29	0.22	0.25	0.11	0.20	0.45
965	0.18	0.04	0.14	0.24	0.06	0.03	0.03	0.37
1020	0.26	0.19	0.29	0.19	0.21	0.12	0.18	0.39
1026	0.18	0.02	0.08	0.26	0.07	0.05	0.01	0.41
1051	0.32	0.26	0.48	0.17	0.31	0.20	0.26	0.36
1110	0.25	0.17	0.30	0.22	0.20	0.10	0.15	0.35
1115	0.40	0.41	0.54	0.20	0.45	0.36	0.44	0.32
1134	0.30	0.26	0.38	0.18	0.29	0.20	0.25	0.36

TABLE 16.—*Continued*

STATION	STATION							
	256	310	333	350	354	374	406	442
2	0.33	0.31	0.31	0.33	0.41	0.37	0.42	0.34
14	0.50	0.36	0.33	0.33	0.36	0.26	0.28	0.29
21	0.53	0.41	0.31	0.28	0.36	0.22	0.27	0.23
54	0.41	0.24	0.50	0.58	0.41	0.43	0.40	0.51
65	0.40	0.23	0.54	0.68	0.52	0.42	0.46	0.61
73.2	0.35	0.27	0.17	0.13	0.25	0.23	0.24	0.14
92	0.34	0.20	0.56	0.72	0.49	0.47	0.48	0.64
92.1	0.43	0.40	0.19	0.13	0.27	0.23	0.23	0.13
103	0.31	0.42	0.56	0.49	0.44	0.34	0.53	0.50
118	0.13	0.24	0.67	0.66	0.47	0.40	0.56	0.68
142	0.31	0.19	0.58	0.78	0.56	0.45	0.53	0.70
147	0.41	0.34	0.24	0.14	0.30	0.14	0.24	0.10
175.1	0.20	0.30	0.56	0.71	0.50	0.44	0.62	0.71
194	0.05	0.18	0.58	0.67	0.44	0.32	0.58	0.68
217	0.12	0.24	0.61	0.74	0.54	0.38	0.60	0.73
250	0.59	0.56	0.30	0.22	0.43	0.26	0.38	0.18
256	1.00	0.57	0.32	0.24	0.42	0.26	0.30	0.17
310	0.57	1.00	0.34	0.23	0.45	0.33	0.51	0.24
333	0.32	0.34	1.00	0.64	0.52	0.46	0.65	0.65
350	0.24	0.23	0.64	1.00	0.70	0.46	0.67	0.86
354	0.42	0.45	0.52	0.70	1.00	0.38	0.63	0.63
374	0.26	0.33	0.46	0.46	0.38	1.00	0.55	0.50
406	0.30	0.51	0.65	0.67	0.63	0.55	1.00	0.68
442	0.17	0.24	0.65	0.86	0.63	0.50	0.68	1.00
483	0.46	0.64	0.55	0.56	0.63	0.34	0.68	0.52
511	0.54	0.60	0.32	0.22	0.40	0.27	0.44	0.22
529	0.56	0.66	0.35	0.25	0.43	0.26	0.47	0.24
540	0.35	0.40	0.42	0.42	0.40	0.33	0.43	0.33
562	0.42	0.59	0.46	0.44	0.49	0.42	0.61	0.42
650	0.59	0.53	0.23	0.12	0.33	0.23	0.27	0.09
684	0.53	0.55	0.35	0.26	0.48	0.32	0.39	0.26
690	0.51	0.56	0.23	0.16	0.34	0.24	0.31	0.14
707	0.46	0.43	0.36	0.36	0.42	0.40	0.47	0.30
741	0.55	0.49	0.24	0.20	0.33	0.23	0.31	0.13
782	0.39	0.32	0.55	0.71	0.61	0.44	0.60	0.65
794	0.51	0.55	0.27	0.26	0.42	0.27	0.38	0.21
798	0.52	0.46	0.20	0.12	0.29	0.18	0.24	0.05
847	0.49	0.50	0.30	0.27	0.40	0.26	0.38	0.20
863	0.58	0.50	0.28	0.25	0.37	0.36	0.35	0.18
883	0.39	0.31	0.47	0.67	0.57	0.49	0.53	0.61
912	0.49	0.44	0.27	0.31	0.43	0.27	0.35	0.26
965	0.44	0.33	0.14	0.11	0.24	0.13	0.19	0.04
1020	0.46	0.36	0.29	0.31	0.37	0.22	0.32	0.24
1026	0.44	0.37	0.12	0.07	0.23	0.07	0.14	0.01
1051	0.43	0.28	0.36	0.47	0.43	0.40	0.35	0.39
1110	0.47	0.30	0.28	0.31	0.34	0.15	0.25	0.20
1115	0.32	0.25	0.47	0.58	0.47	0.39	0.46	0.52
1134	0.41	0.32	0.35	0.41	0.42	0.29	0.35	0.31

TABLE 16.—*Continued*

STATION	STATION 483	511	529	540	562	650	684	690
2	0.33	0.36	0.28	0.20	0.27	0.32	0.37	0.24
14	0.38	0.41	0.41	0.19	0.31	0.36	0.38	0.36
21	0.42	0.43	0.48	0.24	0.34	0.41	0.41	0.44
54	0.38	0.27	0.32	0.30	0.29	0.22	0.28	0.25
65	0.41	0.24	0.26	0.31	0.32	0.18	0.29	0.18
73.2	0.22	0.37	0.29	0.09	0.27	0.36	0.34	0.30
92	0.38	0.19	0.22	0.28	0.29	0.13	0.23	0.15
92.1	0.32	0.47	0.39	0.16	0.30	0.48	0.43	0.42
103	0.52	0.35	0.40	0.37	0.46	0.28	0.35	0.31
118	0.50	0.19	0.26	0.35	0.39	0.06	0.21	0.12
142	0.43	0.19	0.23	0.33	0.32	0.10	0.25	0.12
147	0.38	0.38	0.42	0.26	0.29	0.40	0.43	0.38
175.1	0.53	0.23	0.29	0.38	0.46	0.11	0.23	0.18
194	0.42	0.13	0.18	0.31	0.37	0.01	0.14	0.08
217	0.53	0.19	0.25	0.38	0.41	0.06	0.24	0.14
250	0.51	0.58	0.52	0.33	0.43	0.58	0.57	0.53
256	0.46	0.54	0.56	0.35	0.42	0.59	0.53	0.51
310	0.64	0.60	0.66	0.40	0.59	0.53	0.55	0.56
333	0.55	0.32	0.35	0.42	0.46	0.23	0.35	0.23
350	0.56	0.22	0.25	0.42	0.44	0.12	0.26	0.16
354	0.63	0.40	0.43	0.40	0.49	0.33	0.48	0.34
374	0.34	0.27	0.26	0.33	0.42	0.23	0.32	0.24
406	0.68	0.44	0.47	0.43	0.61	0.27	0.39	0.31
442	0.52	0.22	0.24	0.33	0.42	0.09	0.26	0.14
483	1.00	0.53	0.58	0.60	0.67	0.45	0.56	0.50
511	0.53	1.00	0.76	0.36	0.66	0.70	0.64	0.61
529	0.58	0.76	1.00	0.45	0.72	0.66	0.61	0.64
540	0.60	0.36	0.45	1.00	0.62	0.34	0.39	0.35
562	0.67	0.66	0.72	0.62	1.00	0.49	0.54	0.50
650	0.45	0.70	0.66	0.34	0.49	1.00	0.68	0.75
684	0.56	0.64	0.61	0.39	0.54	0.68	1.00	0.68
690	0.50	0.61	0.64	0.35	0.50	0.75	0.68	1.00
707	0.46	0.61	0.55	0.36	0.56	0.50	0.48	0.48
741	0.45	0.61	0.57	0.30	0.51	0.56	0.51	0.55
782	0.50	0.45	0.42	0.38	0.52	0.34	0.46	0.37
794	0.55	0.64	0.65	0.42	0.61	0.57	0.58	0.61
798	0.39	0.56	0.52	0.25	0.44	0.54	0.48	0.52
847	0.51	0.60	0.59	0.37	0.54	0.53	0.52	0.53
863	0.43	0.61	0.56	0.34	0.50	0.57	0.52	0.53
883	0.48	0.37	0.35	0.37	0.48	0.27	0.44	0.33
912	0.46	0.53	0.50	0.31	0.46	0.45	0.43	0.46
965	0.33	0.46	0.42	0.19	0.30	0.47	0.37	0.42
1020	0.40	0.47	0.40	0.26	0.39	0.42	0.36	0.41
1026	0.30	0.50	0.42	0.16	0.30	0.46	0.38	0.40
1051	0.36	0.38	0.35	0.31	0.35	0.36	0.43	0.34
1110	0.37	0.42	0.38	0.27	0.34	0.39	0.33	0.34
1115	0.49	0.31	0.32	0.41	0.45	0.25	0.30	0.24
1134	0.41	0.42	0.38	0.24	0.39	0.38	0.36	0.36

TABLE 16.—*Continued*

STATION	STATION							
	707	741	782	794	798	847	863	883
2	0.39	0.30	0.37	0.27	0.27	0.34	0.41	0.37
14	0.44	0.44	0.41	0.46	0.47	0.48	0.48	0.38
21	0.45	0.49	0.37	0.54	0.52	0.52	0.50	0.35
54	0.39	0.30	0.52	0.32	0.27	0.33	0.39	0.48
65	0.40	0.28	0.60	0.32	0.23	0.34	0.33	0.58
73.2	0.36	0.36	0.25	0.27	0.31	0.33	0.37	0.28
92	0.37	0.24	0.61	0.27	0.19	0.27	0.31	0.60
92.1	0.37	0.45	0.27	0.39	0.43	0.40	0.43	0.26
103	0.32	0.26	0.41	0.31	0.24	0.34	0.34	0.39
118	0.24	0.18	0.45	0.23	0.14	0.23	0.12	0.40
142	0.33	0.20	0.61	0.24	0.15	0.25	0.25	0.58
147	0.24	0.33	0.16	0.31	0.25	0.32	0.27	0.21
175.1	0.29	0.20	0.50	0.25	0.13	0.24	0.20	0.49
194	0.18	0.05	0.45	0.09	0.02	0.13	0.08	0.40
217	0.25	0.16	0.49	0.23	0.12	0.22	0.11	0.44
250	0.41	0.51	0.36	0.47	0.47	0.49	0.49	0.33
256	0.46	0.55	0.39	0.51	0.52	0.49	0.58	0.39
310	0.43	0.49	0.32	0.55	0.46	0.50	0.50	0.31
333	0.36	0.24	0.55	0.27	0.20	0.30	0.28	0.47
350	0.36	0.20	0.71	0.26	0.12	0.27	0.25	0.67
354	0.42	0.33	0.61	0.42	0.29	0.40	0.37	0.57
374	0.40	0.23	0.44	0.27	0.18	0.26	0.36	0.49
406	0.47	0.31	0.60	0.38	0.24	0.38	0.35	0.53
442	0.30	0.13	0.65	0.21	0.05	0.20	0.18	0.61
483	0.46	0.45	0.50	0.55	0.39	0.51	0.43	0.48
511	0.61	0.61	0.45	0.64	0.56	0.60	0.61	0.37
529	0.55	0.57	0.42	0.65	0.52	0.59	0.56	0.35
540	0.36	0.30	0.38	0.42	0.25	0.37	0.34	0.37
562	0.56	0.51	0.52	0.61	0.44	0.54	0.50	0.48
650	0.50	0.56	0.34	0.57	0.54	0.53	0.57	0.27
684	0.48	0.51	0.46	0.58	0.48	0.52	0.52	0.44
690	0.48	0.55	0.37	0.61	0.52	0.53	0.53	0.33
707	1.00	0.76	0.68	0.74	0.69	0.74	0.74	0.55
741	0.76	1.00	0.51	0.78	0.83	0.75	0.75	0.43
782	0.68	0.51	1.00	0.55	0.42	0.55	0.52	0.82
794	0.74	0.78	0.55	1.00	0.72	0.72	0.68	0.50
798	0.69	0.83	0.42	0.72	1.00	0.78	0.75	0.38
847	0.74	0.75	0.55	0.72	0.78	1.00	0.79	0.51
863	0.74	0.75	0.52	0.68	0.75	0.79	1.00	0.52
883	0.55	0.43	0.82	0.50	0.38	0.51	0.52	1.00
912	0.63	0.66	0.51	0.68	0.64	0.68	0.68	0.53
965	0.50	0.58	0.34	0.49	0.59	0.55	0.58	0.30
1020	0.54	0.56	0.50	0.51	0.55	0.57	0.58	0.48
1026	0.44	0.54	0.27	0.44	0.57	0.55	0.53	0.25
1051	0.53	0.45	0.66	0.42	0.42	0.52	0.56	0.66
1110	0.48	0.51	0.44	0.48	0.51	0.52	0.52	0.41
1115	0.43	0.37	0.63	0.39	0.28	0.45	0.42	0.62
1134	0.50	0.51	0.54	0.49	0.48	0.55	0.50	0.52

TABLE 16.—*Continued*

STATION	STATION							
	912	965	4020	1026	1051	1110	1115	1134
2	0.37	0.24	0.32	0.23	0.39	0.29	0.38	0.32
14	0.46	0.43	0.45	0.39	0.44	0.43	0.34	0.42
21	0.50	0.43	0.46	0.40	0.41	0.47	0.30	0.42
54	0.32	0.25	0.33	0.23	0.52	0.35	0.49	0.39
65	0.38	0.21	0.38	0.18	0.56	0.39	0.54	0.43
73.2	0.34	0.26	0.29	0.33	0.29	0.25	0.20	0.29
92	0.31	0.18	0.32	0.13	0.52	0.32	0.54	0.40
92.1	0.39	0.34	0.33	0.38	0.26	0.30	0.21	0.29
103	0.30	0.18	0.26	0.18	0.32	0.25	0.40	0.30
118	0.20	0.04	0.19	0.02	0.26	0.17	0.41	0.26
142	0.29	0.14	0.29	0.08	0.48	0.30	0.54	0.38
147	0.22	0.24	0.19	0.26	0.17	0.22	0.20	0.18
175.1	0.25	0.06	0.21	0.07	0.31	0.20	0.45	0.29
194	0.11	0.03	0.12	0.05	0.20	0.10	0.36	0.20
217	0.20	0.03	0.18	0.01	0.26	0.15	0.44	0.25
250	0.45	0.37	0.39	0.41	0.36	0.35	0.32	0.36
256	0.49	0.44	0.46	0.44	0.43	0.47	0.32	0.41
310	0.44	0.33	0.36	0.37	0.28	0.30	0.25	0.32
333	0.27	0.14	0.29	0.12	0.36	0.28	0.47	0.35
350	0.31	0.11	0.31	0.07	0.47	0.31	0.58	0.41
354	0.43	0.24	0.37	0.23	0.43	0.34	0.47	0.42
374	0.27	0.13	0.22	0.07	0.40	0.15	0.39	0.29
406	0.35	0.19	0.32	0.14	0.35	0.25	0.46	0.35
442	0.26	0.04	0.24	0.01	0.39	0.20	0.52	0.31
483	0.46	0.33	0.40	0.30	0.36	0.37	0.49	0.41
511	0.53	0.46	0.47	0.50	0.38	0.42	0.31	0.42
529	0.50	0.42	0.40	0.42	0.35	0.38	0.32	0.38
540	0.31	0.19	0.26	0.16	0.31	0.27	0.41	0.24
562	0.46	0.30	0.39	0.30	0.35	0.34	0.45	0.39
650	0.45	0.47	0.42	0.46	0.36	0.39	0.25	0.38
684	0.43	0.37	0.36	0.38	0.43	0.33	0.30	0.36
690	0.46	0.42	0.41	0.40	0.34	0.34	0.24	0.36
707	0.63	0.50	0.54	0.44	0.53	0.48	0.43	0.50
741	0.66	0.58	0.56	0.54	0.45	0.51	0.37	0.51
782	0.51	0.34	0.50	0.27	0.66	0.44	0.63	0.54
794	0.68	0.49	0.51	0.44	0.42	0.48	0.39	0.49
798	0.64	0.59	0.55	0.57	0.42	0.51	0.28	0.48
847	0.68	0.55	0.57	0.55	0.52	0.52	0.45	0.55
863	0.68	0.58	0.58	0.53	0.56	0.52	0.42	0.50
883	0.53	0.30	0.48	0.25	0.66	0.41	0.62	0.52
912	1.00	0.49	0.57	0.44	0.53	0.55	0.50	0.55
965	0.49	1.00	0.67	0.76	0.50	0.62	0.33	0.54
1020	0.57	0.67	1.00	0.62	0.67	0.82	0.53	0.72
1026	0.44	0.76	0.62	1.00	0.45	0.59	0.31	0.55
1051	0.53	0.50	0.67	0.45	1.00	0.61	0.65	0.68
1110	0.55	0.62	0.82	0.59	0.61	1.00	0.52	0.72
1115	0.50	0.33	0.53	0.31	0.65	0.52	1.00	0.67
1134	0.55	0.54	0.72	0.55	0.68	0.72	0.67	1.00

TABLE 17. COMPARISON OF RUN LENGTHS OF BELOW MEDIAN ANNUAL RAINFALL WITH RUNS OF BELOW MEDIAN RANDOM NUMBERS, STA. 741, ‘EWA MILL, O‘AHU (96 YR OF DATA)

	RUN LENGTH (yr)								
	1	2	3	4	5	6	7	8	9
Station 741	13	5	1	2	1	0	0	1	0
Random (1)	13	6	3	1	2	0	1	0	0
Random (2)	14	8	2	4	0	0	0	0	0
Random (3)	12	8	3	3	0	0	1	0	0
Random (4)	6	5	7	2	1	1	0	0	0
Random (5)	12	6	2	3	0	0	0	0	0
Random (6)	13	4	3	1	1	1	0	0	1
Random (7)	14	7	3	1	0	0	0	0	0
Random (8)	15	9	2	2	0	1	0	0	0
Random (9)	14	4	2	1	0	0	1	0	0
Random (10)	8	6	2	2	3	0	0	0	0
Random (10)	8	6	2	2	3	0	0	0	0

TABLE 18. COMPARISON OF RUN LENGTHS OF BELOW MEDIAN ANNUAL RAINFALL WITH RUNS OF BELOW MEDIAN RANDOM NUMBERS, STA. 782, LOWER LAUKAHA, O‘AHU (97 YR OF DATA)

	RUN LENGTH (yr)						
	1	2	3	4	5	6	7
Station 782	11	6	3	1	1	0	1
Random (1)	15	3	6	2	0	0	0
Random (2)	9	11	3	0	1	0	0
Random (3)	10	7	4	1	0	1	0
Random (4)	10	7	2	3	0	1	0
Random (5)	15	7	4	2	0	0	0
Random (6)	13	5	4	1	1	0	0
Random (7)	9	9	1	3	2	0	0
Random (8)	7	7	4	2	0	1	0
Random (9)	15	4	4	2	0	0	0
Random (10)	13	5	4	2	0	0	0

TABLE 19. COMPARISON OF RUN LENGTHS OF BELOW MEDIAN MONTHLY RAINFALL WITH RUNS OF BELOW MEDIAN RANDOM NUMBERS, STA. 741, ‘EWA MILL, O‘AHU (96 YR OF DATA)

	RUN LENGTH (yr)													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Station 782	109	57	39	14	11	10	4	2	1	0	0	1	0	0
Random (1)	143	77	34	19	4	11	2	1	1	0	0	0	0	0
Random (2)	157	63	36	17	13	6	1	2	0	0	0	0	0	0
Random (3)	164	59	35	14	11	7	1	0	1	0	0	1	0	0
Random (4)	130	73	31	18	6	4	2	5	0	0	0	0	0	1
Random (5)	156	75	33	13	6	8	2	0	0	0	1	0	0	0
Random (6)	130	90	37	14	7	6	2	0	1	0	0	0	0	0
Random (7)	146	83	32	20	3	3	3	1	0	0	0	0	0	0
Random (8)	163	62	32	19	9	7	1	2	0	0	0	0	0	0
Random (9)	150	77	30	14	10	6	4	2	0	0	0	0	0	0
Random (10)	145	85	35	18	7	4	2	0	1	0	0	0	0	0

TABLE 20. COMPARISON OF RUN LENGTHS OF BELOW MEDIAN MONTHLY RAINFALL WITH RUNS OF BELOW MEDIAN RANDOM NUMBERS, STA. 782, LOWER LAUKAHA, O‘AHU (97 YR OF DATA)

	RUN LENGTH (yr)											
	1	2	3	4	5	6	7	8	9	10	11	12
Station 782	113	53	31	19	13	4	4	0	3	1	2	1
Random (1)	159	69	33	21	6	4	2	1	0	0	0	0
Random (2)	156	75	32	12	12	4	1	1	0	1	0	0
Random (3)	147	74	37	21	9	6	1	0	1	1	0	0
Random (4)	171	63	41	13	11	3	2	1	0	0	0	0
Random (5)	164	79	31	11	7	4	3	2	0	0	1	0
Random (6)	180	53	39	17	8	4	1	1	1	0	0	0
Random (7)	109	85	37	21	12	3	1	1	0	2	0	0
Random (8)	131	82	40	14	8	3	5	2	1	0	0	0
Random (9)	158	71	31	17	10	5	2	0	0	0	0	0
Random (10)	152	77	30	17	9	4	6	1	0	0	0	0
Random (10)	152	77	30	17	9	4	6	1	0	0	0	0

TABLE 21. CONDITIONAL PROBABILITIES (%) OF DROUGHT ONSET IN A SPECIFIC MONTH AND ITS CONTINUATION ON O'AHU

MONTH	ADDITIONAL MONTHS DURATION							
	1	2	3	4	5	6	7	8
Jan	58	42	33	17	0	0	0	0
Feb	44	22	11	0	0	0	0	0
Mar	27	13	7	0	0	0	0	0
Apr	33	0	0	0	0	0	0	0
May	36	27	27	27	27	9	9	9
June	38	13	0	0	0	0	0	0
July	67	22	11	0	0	0	0	0
Aug	56	44	44	33	33	33	22	0
Sep	56	22	11	11	0	0	0	0
Oct	0	0	0	0	0	0	0	0
Nov	50	25	19	19	0	0	0	0
Dec	58	33	17	17	8	0	0	0
All	47	25	17	12	6	3	3	1

NOTE: Drought defined as any month with BMDI $\leq$ -2, and given that a drought begins in a specific month, probability of continuing for x additional months; "all" indicates probabilities for all droughts regardless of starting month.

TABLE 22. CONDITIONAL PROBABILITIES (%) OF DROUGHT OCCURRENCE IN A SPECIFIC MONTH AND ITS CONTINUATION ON O'AHU

MONTH	ADDITIONAL MONTHS DURATION							
	1	2	3	4	5	6	7	8
Jan	61	43	21	11	0	0	0	0
Feb	62	31	15	0	0	0	0	0
Mar	39	19	3	0	0	0	0	0
Apr	44	6	0	0	0	0	0	0
May	26	16	16	16	16	5	5	5
June	46	31	23	23	8	8	8	0
July	67	33	27	7	7	7	0	0
Aug	53	42	26	21	21	16	11	0
Sep	68	37	26	26	16	11	0	0
Oct	50	36	36	21	14	0	0	0
Nov	57	39	26	22	0	0	0	0
Dec	64	40	28	8	4	0	0	0

NOTE: Drought defined as any month with BMDI $\leq$ -2, and given that an event exists in a specific month, regardless of previous months, probability of continuing for x additional months.

occurrence. Specifically, can the existence of a drought event tell us something about the likelihood of its continuation? We approached this question by examining the conditional probabilities of continuing runs of below median rainfall and of continuing an in-progress island drought event using the BMDI. In the second case, the season of occurrence was also specified in the condition.

Figures 37–40 illustrate, for Stations 741 and 782 on O'ahu, the conditional probabilities of continuing below median rainfall given that below median rainfall has been experienced for a certain number of months. Referring to the uppermost line (labeled "1 mo") in Figure 37, the value on the ordinate gives the probability that an in-progress dry spell at Station 741 will continue for at least one additional month given that it has experienced below-median rainfall for the duration indicated on the abscissa. The next lower line (2 mo) gives the probability of continuation for at least two additional months, and so forth. For example, given that rainfall at Station 741 has been below the median for one month, the probability that it will remain below normal for at least one more month is 56%, for at least two more months is 33%. Given that a dry spell has been in progress for four months, the probability of continuing another month is 67%.

The two graphs indicate that dry weather is more likely to occur next month if the current month is dry. For both stations and for nearly every duration and continuation condition, the probability exceeds that of a random series. Since the median defines the point for which higher or lower values have equal frequencies, the probability of continuing one additional month below median would always be 50% if the series were random. Likewise, the probability, in percent, of continuing 2, 3, 4, 5, 6, 7, and 8 months would be respectively, 25, 12.5, 6.3, 3.1, 1.6, 0.8, 0.4, 0.2, 0.1, 0.05, and 0.02 for random series. The probabilities for these two stations exceed these values in nearly all cases. Since the longest run of below-median rainfall at each station was 12 months, the lines all drop to 0% probability when the sum of in-progress duration and continuation period exceeds 12 months.

Defining drought as any month during which the BMDI is -2.0 or less, the conditional probabilities of event continuation were computed for O'ahu, for droughts that begin in a given month (Table 21). No O'ahu droughts began in October. Given that a drought began in January, the probability of it continuing at least through February is 58%, at least through March is 42%, and so on. O'ahu droughts beginning in January, July, August, September, or December have better than even chances of continuing for one or more additional months. The last row in the table (labeled "All") gives probabilities for continuation regardless of the month.

In Table 22, probabilities are given for continuation of events existing during a certain month, regardless of when they began. Drought events existing during any month between July and February have at least an even chance of continuing an additional month or more.

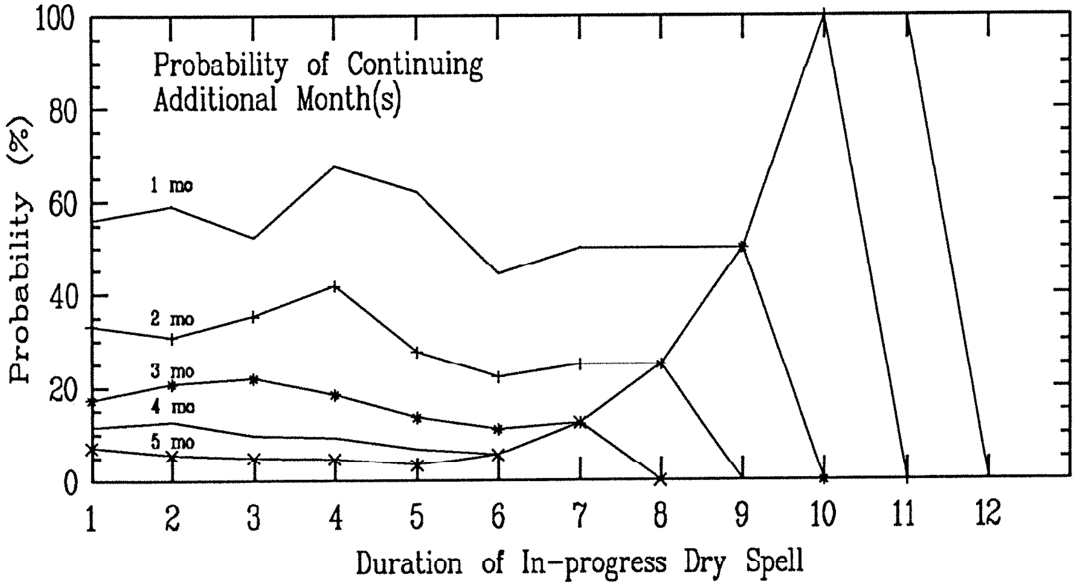


Figure 37. Conditional probabilities of continuing in-progress dry spell for 1–5 additional mo, Sta. 741

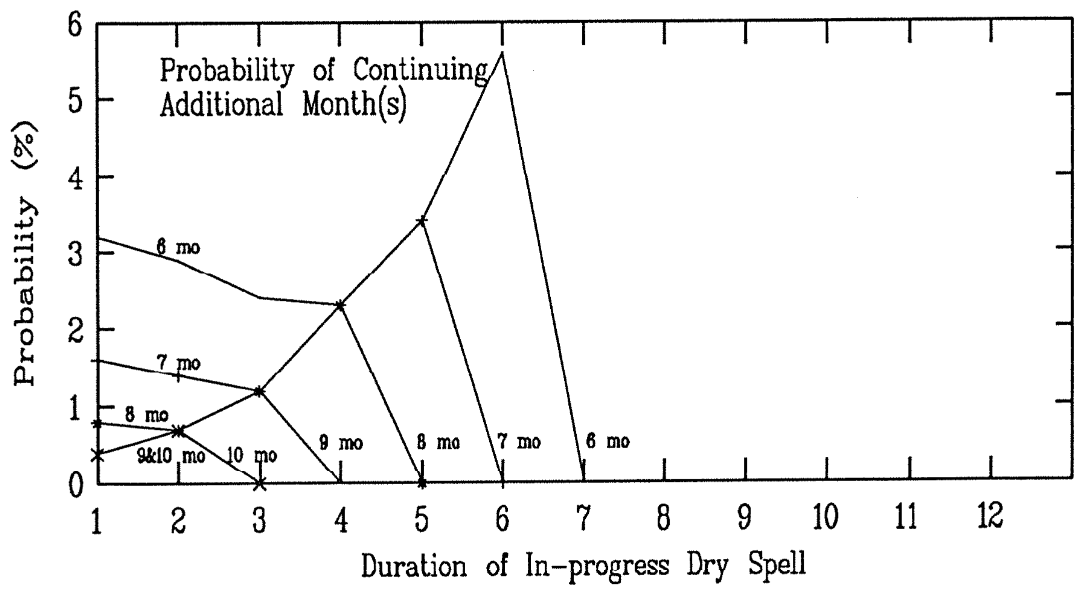


Figure 38. Conditional probabilities of continuing in-progress dry spell for 6–10 additional mo, Sta. 741

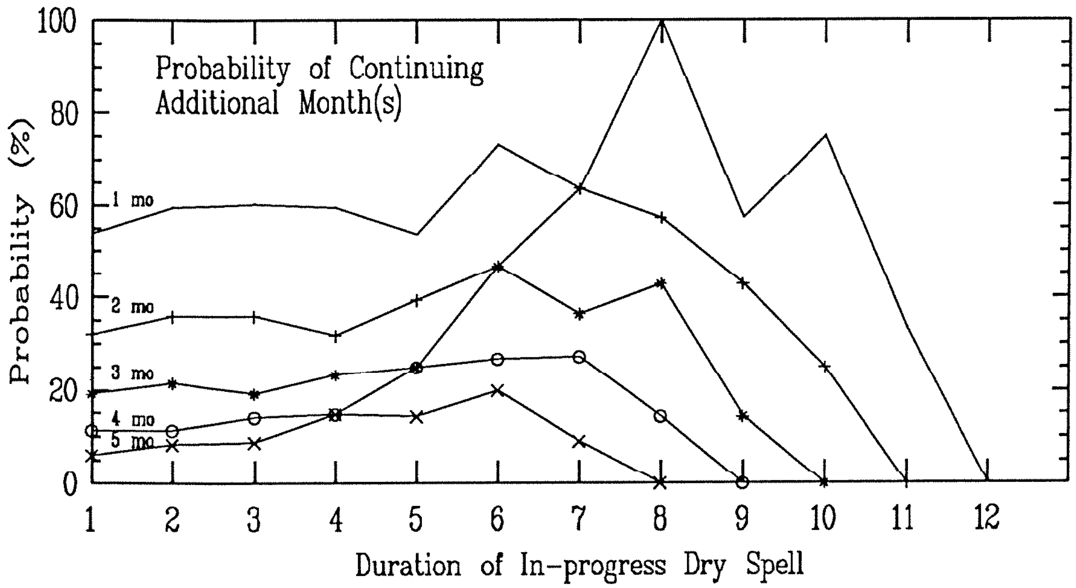


Figure 39. Conditional probabilities of continuing in-progress dry spell for 1–5 additional mo, Sta. 782

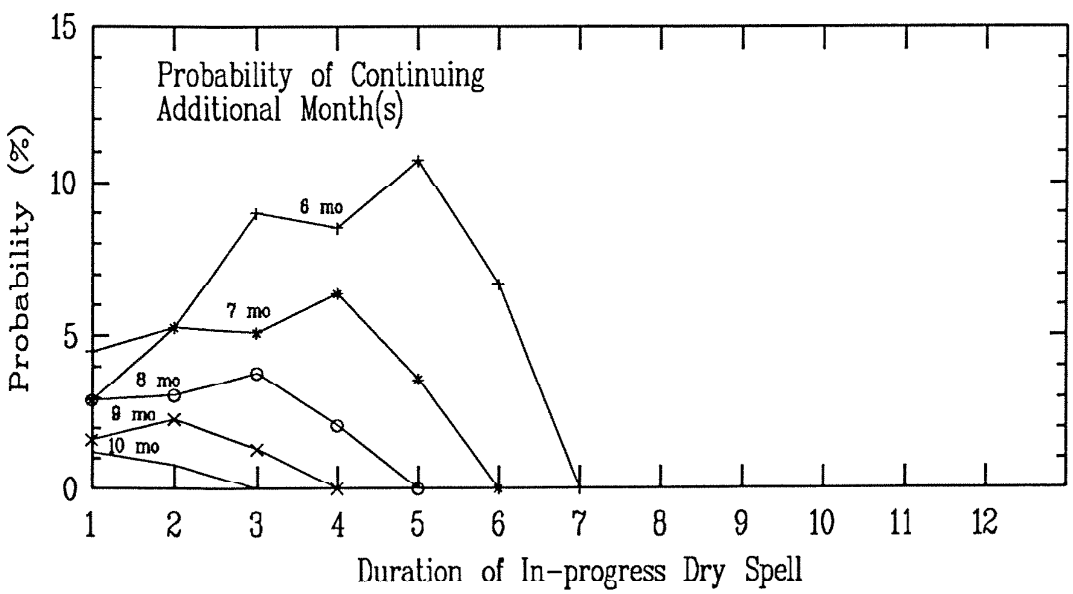


Figure 40. Conditional probabilities of continuing in-progress dry spell for 6–10 additional mo, Sta. 782

ENSO and Drought in Hawai'i

El Niño, the anomalous warming of the eastern equatorial Pacific sea surface, and the Southern Oscillation, the seesaw in atmospheric mass between the eastern and western equatorial Pacific, are two parts of a global-scale oceanic-atmospheric phenomenon now known as ENSO (El Niño-Southern Oscillation). ENSO has been associated with winter drought in Hawai'i (Meisner 1976; Wright 1979; Horel and Wallace 1981; Lyons 1982; and Chu 1989). Meisner found that winter rainfall in Hawai'i was negatively correlated with contemporaneous sea surface temperature (SST) in the eastern equatorial Pacific. However, he found higher correlation with differences between North Pacific SSTs and noted that the conditions linking SST and rainfall appear to change reducing the overall predictive value. Horel and Wallace (1981) postulated that the North Pacific jet stream is shifted southward and intensified during periods of very low Southern Oscillation Index (SOI) (corresponding to an ENSO event). Yeh, carson, and Marciano (1950) had earlier found that Hawaiian winter rainfall was related positively to the latitude and inversely to the strength of the jet stream. Lyons (1982) confirmed that deficient trade wind rainfall, presumably associated with a southward shift of the Pacific subtropical anticyclone, produces dry winters in most but not all ENSO years. He pointed out, as others have, that extremely dry winters also occur in Hawai'i during non-ENSO years. Lyons also showed that above-normal summer rainfall from tropical disturbances tends to be associated with warm eastern equatorial SST. Chu (1989) found that dry winters in Hawai'i are preceded by low SOI values beginning in March of the previous year. This finding suggests that prediction of winter drought on the basis of SOI may be possible.

To illustrate the relationship between rainfall and ENSO, Figures 41–42 shows the average monthly BMDI for the state in comparison with eastern equatorial Pacific SST anomalies.* El Niño is a period of prolonged positive SST anomalies. Note that the statewide droughts of July-November 1953, January-February 1973, December 1976-February 1977, and February-April 1983 correspond with El Niños. However, the El Niño year of 1965 was relatively wet in the islands. Also, the droughts of August-September 1952, November-December 1962, July-August 1971, June-August 1973, May-September 1975, September 1977-February 1978, and August-October 1984 were not directly associated with warm eastern equatorial SST.

Climate Change and Drought

Throughout this and other drought studies, an important implicit assumption is that the long-term climate is constant. The value of examining past drought occurrences in this context is that

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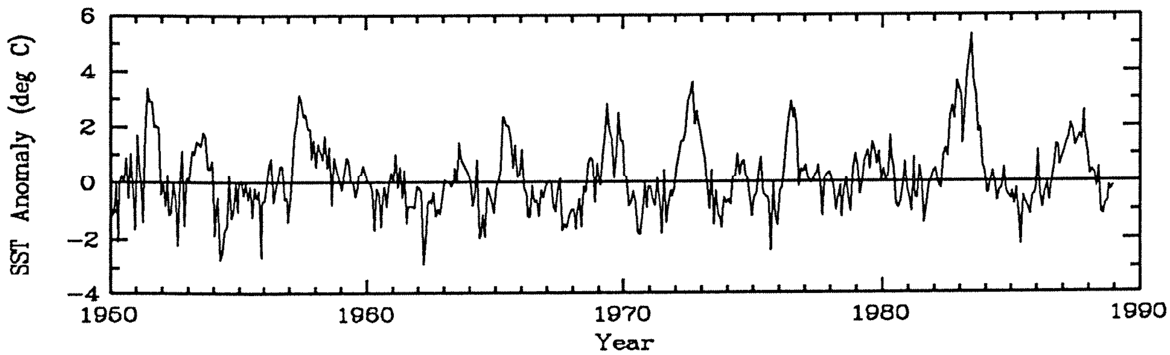
*P.S. Chu (Univ. of Hawaii-Manoa, Dept. of Meteorology 1990: personal communication.)



SOURCE: P.S. Chu (personal communication).

Figure 41. Monthly sea surface temperature anomaly, eastern equatorial Pacific, 1950–1988

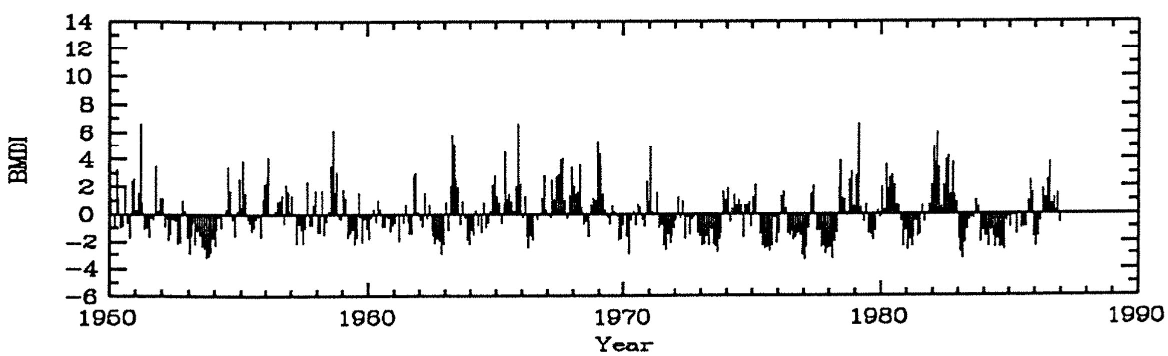


Figure 42. Monthly average BMDI, Hawai'i State, 1950–1986

we expect future droughts to behave similarly and to occur with similar frequency. This so-called stationarity assumption has been seriously questioned in recent years as evidence indicates that global climate may warm significantly due to increasing atmospheric concentrations of carbon dioxide and other radiation-absorbing gases. Future climate warming has a number of serious implications including impacts on the hydrological cycle. Projections of likely climate change under various warming scenarios by general circulation models (GCMs) indicate that some areas of the globe may experience substantial positive or negative change in precipitation. More importantly for drought consideration, rainfall is predicted to become more variable, producing more frequent and severe extremes, both wet and dry. GCMs predict slightly higher rainfall with warming for the oceanic region in which Hawai'i lies (Wilson and Mitchell 1987). GCM estimates are made on a coarse grid and because of the strong dependence of rainfall on the wind direction and topography, accurate projections of rainfall change in Hawai'i resulting from global warming are not yet possible. Response of Hawai'i rainfall to warming will likely be highly site specific and not necessarily correspond in magnitude or direction with changes in regional oceanic rainfall.

While future changes in rainfall in Hawai'i are difficult to project, the impact of warming on evaporation rates is a more tractable problem. Because of the effects of temperature on the controls of evaporation, especially relative humidity, the environmental demand for water under a 2°C temperature increase would likely be about 8% greater than at present (Giambelluca 1989). Such an increase would lead to a higher demand for water for urban lawn sprinkling and agricultural irrigation while reducing supply in the form of groundwater recharge. A recent analysis of the impacts of future warming on the Pearl Harbor basin of O'ahu (Giambelluca 1989) found that water supply would be negatively affected even if rainfall increased by 10%. By narrowing the gap between supply and demand, warming would probably lead to more frequent and severe drought impacts.

DESCRIPTIVE ACCOUNTS OF OCCURRENCE AND IMPACTS OF DROUGHT

Based on newspaper accounts, plantation records, and other relevant published and unpublished sources, all available references to drought occurrence in Hawai'i since the year 1860 have been complied and entered into a computer database. These accounts of past droughts offer an independent method of assessing drought occurrence and characteristics. We used this descriptive database to investigate two questions: (1) How valuable are historical descriptive accounts in identifying the frequency and characteristics of drought in a region? and (2) What are the actual impacts associated with droughts of different severity as determined by rainfall-based indices? Both questions were approached by identifying droughts and rating their severity solely on the basis of the drought descriptions and comparing the results with those obtained using the BMDI.

The drought description chronology used in this analysis was obtained primarily from two sources. Saul Price of the National Weather Service, Honolulu, and Peter Matsunaga, former graduate student in Geography at the University of Hawaii, each compiled data bases of drought reports which were made available for this study. Many of the compiled reports were based on references to rainfall measurements. Such reports were not included so that the descriptive chronology would consist only of noninstrumental observations of rainfall deficit and associated impacts.

Table 23 lists, for each drought report, the beginning and ending date (if available) of the reported event, the islands affected, and the types of impacts reported (water supply, crop, livestock, or fire). In Appendix Figures D.16–D.29, drought reports beginning in 1880 are plotted above the time axis and the corresponding monthly BMDI values below. As a crude indication of magnitude, a reported drought is classified extreme if the report contains language such as "the worst drought in memory," or if a state of emergency was declared; otherwise it is classified moderate. The BMDI index is plotted only if it is less than -1.5. While there is general agreement between the two time series, there are some instances of a report without a BMDI less than -1.5 and numerous cases of a low index and no report. Some tendency is apparent for drought reports to lag a month or two behind the index.

Whenever a series of reports was obviously associated with a single drought, these were grouped and the duration of the event identified. All affected islands and all impacts mentioned in the various reports are put together to describe each event. These events are tabulated and presented earlier in this report (see Table 1). To compare the descriptive events with those determined objectively, both are plotted in Figure 43 on a time axis with the descriptive events depicted above the axis and the BMDI-derived events below. BMDI events are determined as previously described and presented, except that all events are shown regardless of the size of the rain gage network on which it was based. Here again, the correspondence between the two drought event indices is good. Mismatches are primarily cases where events identified by the BMDI index were not associated with any reports of drought.

The comparisons made in Appendix Figures D.16–D.29 and Figure 43 generally confirm that the BMDI index is able to identify the important droughts in the state. The many instances of BMDI-derived events and no drought report, illustrate the difficulty of using subjective data to analyze past events. The "missing" reports may be explained in several ways. First, no amount of searching can ever guarantee that all reports are discovered, especially those from decades ago. It is likely that many more drought descriptions were made but simply were not

TABLE 23. DESCRIPTIVE ACCOUNTS OF DROUGHT IN HAWAI'I, 1856–1986

DROUGHT PERIOD From	To	ISLANDS AFFECTED*						IMPACT†		
1856									C	
1860 Oct						Oa				
1861 Nov						Oa		W		
1866 Sep			Ma			Oa	Ka			
1869 Feb						Oa		W		
1869 Mar		Ha						W	C	
1872 Aug	1872 Sep		Ma					W	C	L
1872 Sep						Oa				
1873 Feb		Ha						W		
1873 June	1873 July		Ma						C	L
1873 July	1873 Oct					Oa				
1873 Sep		Ha							C	
1873 Nov						Oa				
1875 Sep	1876 Feb		Ma							
1876 May		Ha						W	C	
1876 July	1876 Oct					Oa				
1876 July	1876 Oct		Ma			Oa		W		L
1877 Nov	1878 Mar	Ha						W	C	
1878 Jan	1878 Apr					Oa			C	L
1878 Mar			Ma						C	L
1881 June		Ha								
1881 Oct		Ha	Ma						C	
1881 Nov			Ma				Ka	W	C	
1882 Mar		Ha						W		
1882 May		Ha						W		
1882 Nov		Ha								
1883 Nov		Ha		Mo						L
1884 Mar		Ha						W		
1886 July	1886 Aug	Ha	Ma	Mo	La	Oa	Ka			L
1887 June		Ha								
1889 Jan			Ma							
1889 Feb		Ha				Oa			C	
1889 Mar							Ka			
1889 Apr		Ha								L
1889 June		Ha								

DROUGHT PERIOD From	To	ISLANDS AFFECTED*					IMPACT†			
1889 July		Ha	Ma		Oa			C	L	
1891 Aug		Ha							L	
1892 Apr		Ha					W			
1892 June		Ha								
1892 Aug	1892 Sep		Ma					C		
1892 Sep						Ka				
1893 Aug			Ma						L	
1893 Sep		Ha					W	C	L	
1893 Oct						Ka				
1894 May	1894 Nov					Ka				
1894 June		Ha						C		
1895 Apr		Ha								
1897 Apr					Oa					
1897 May		Ha						C		
1897 June	1897 July	Ha					W	C		
1897 Aug			Ma				W			
1898 Apr			Ma					C		
1899 Feb		Ha					W	C		
1900										
1901 June	1901 Sep	Ha	Ma				W	C		F
1902		Ha								F
1902 July	1902 Oct	Ha								F
1902 Oct		Ha								F
1905 Jan	1905 Apr	Ha	Ma		Oa		W	C	L	F
1906 Feb		Ha	Ma	La		Ka				
1907 May		Ha					W			
1908 Feb			Ma				W			
1908 May		Ha	Ma							
1908 Dec	1909 Feb	Ha	Ma			Ka	W		L	
1909 Mar		Ha								
1909 June	1909 Oct	Ha	Ma		Oa					
1910 Sep		Ha	Ma							
1911 Aug			Ma							
1912 July		Ha								
1913										

TABLE 23.—*Continued*

DROUGHT PERIOD From	To	ISLANDS AFFECTED*						IMPACT†			
1913 Sep		Ha	Ma	Mo	La	Oa	Ka				
1914 Feb						Oa					
1915 Mar		Ha									
1916 Aug	1916 Sep					Oa					
1917		Ha	Ma								
1917 Apr	1917 May	Ha							C		
1917 June						Oa					
1917 June	1917 Oct	Ha	Ma					W	C	L	
1917 July				Mo							
1917 Oct				Mo				W			
1918 Sep	1920 Sep										
1919 Feb		Ha									F
1919 Apr			Ma						C		
1919 May	1919 Aug	Ha	Ma	Mo	La	Oa	Ka	W	C	L	
1919 Sep		Ha	Ma						C	L	
1919 Dec	1920 May	Ha	Ma	Mo	La	Oa			C	L	
1920		Ha									
1920 June											
1920 June		Ha	Ma	Mo	La			W	C	L	
1920 July		Ha	Ma	Mo		Oa		W	C	L	
1920 Oct		Ha							C		
1921							Ka				
1921 June		Ha	Ma					W		L	
1921 Aug			Ma	Mo	La	Oa	Ka		C	L	
1921 Sep			Ma	Mo	La					L	
1921 Nov						Oa	Ka		C	L	
1922 June		Ha	Ma	Mo	La	Oa	Ka	W	C	L	
1922 July						Oa					
1922 July		Ha						W	C		
1922 Aug			Ma	Mo					C	L	
1923			Ma								
1923 Mar						Oa					
1923 June		Ha	Ma	Mo	La	Oa	Ka		C		
1924 Jan		Ha	Ma	Mo	La	Oa	Ka	W		L	

DROUGHT PERIOD From	To	ISLANDS AFFECTED*						IMPACT†		
1924 Jan	1924 Feb	Ha	Ma	Mo	La	Oa	Ka			
1924 Feb						Oa		W	C	L
1924 June		Ha							C	
1924 July		Ha	Ma	Mo	La	Oa	Ka	W		
1925 Jan		Ha	Ma	Mo	La	Oa	Ka	W		
1925 Dec		Ha						W		L
1925 Dec	1926 Mar	Ha				Oa	Ka			
1926 Jan	1926 Mar	Ha	Ma	Mo	La	Oa	Ka	W	C	
1926 Jan	1926 May					Oa				
1926 Apr		Ha							C	
1926 May			Ma			Oa	Ka		C	
1927 Feb		Ha						W	C	
1928 Mar		Ha	Ma	Mo	La	Oa		W		
1928 June		Ha						W		
1929 July										
1931 Jan	1931 Mar	Ha						W	C	
1931 Feb		Ha	Ma	Mo	La	Oa	Ka			
1931 June		Ha	Ma	Mo	La	Oa	Ka	W		
1932										
1932 Sep	1932 Oct	Ha							C	L
1933						Oa				
1934 Nov			Ma						C	
1940 Jan	1940 Feb	Ha						W		
1941 Feb						Oa		W	C	
1941 May	1941 June					Oa		W	C	
1941 June		Ha							C	
1944 Apr		Ha	Ma	Mo	La	Oa	Ka		C	L
1944 June						Oa		W		
1945 Apr			Ma	Mo					C	L
1945 Aug		Ha	Ma	Mo	La	Oa	Ka		C	
1949 Apr			Ma						C	
1950 June		Ha	Ma	Mo	La	Oa	Ka			L
1950 Dec	1951 Jan	Ha						W		
1951 Dec	1952 Mar									

TABLE 23.—*Continued*

DROUGHT PERIOD From	To	ISLANDS AFFECTED*						IMPACT†			
1952 Jan	1953 Sep					Oa					
1952 Feb	1952 June			Mo							
1952 Feb	1952 June	Ha									
1952 July	1952 Sep						Ka				
1952 Sep	1952 Dec		Ma	Mo					C		
1952 Sep	1952 Dec	Ha						W			
1953											
1953 Jan			Ma								
1953 Jan		Ha								L	
1953 Jan		Ha	Ma					W	C	L	
1953 Jan	1953 Sep		Ma						C		
1953 Apr						Oa					
1953 June	1953 Aug	Ha	Ma	Mo						L	
1953 Sep		Ha	Ma	Mo	La	Oa	Ka	W	C	L	
1953 Sep			Ma						C		
1953 Oct		Ha	Ma	Mo	La	Oa	Ka	W	C	L	
1953 Oct				Mo						L	
1953 Oct			Ma								
1954 Jan		Ha								L	
1954 Jan		Ha							C	L	
1954 Apr		Ha							C	L	
1954 May				Mo					C		
1954 Nov											F
1957 Jan	1957 Mar		Ma								
1957 June			Ma						C	L	
1957 Oct			Ma					W			
1958 Jan		Ha						W	C		
1958 Jan	1958 Feb	Ha						W			
1958 July	1958 Sep	Ha								L	
1961 Apr	1961 Sep	Ha									
1061 Apr	1961 Sep	Ha							C	L	
1961 May	1961 Oct	Ha								L	
1961 Sep		Ha								L	
1961 Sep		Ha							C		

DROUGHT PERIOD From	To	ISLANDS AFFECTED*						IMPACT†			
1962 Apr	1962 Nov	Ha	Ma						C	L	
1962 June	1962 Nov	Ha						W	C		
1963		Ha									
1963 Jan		Ha									
1963 Jan	1963 Dec	Ha	Ma	Mo	La	Oa	Ka				
1963 Dec		Ha									
1964 July		Ha								L	
1965 Apr		Ha						W	C		
1965 June	1965 Sep										
1965 July		Ha									
1965 July		Ha									
1965 Aug		Ha							C		
1965 Sep		Ha							C		
1965 Sep		Ha						W			
1965 Oct		Ha									
1966 May		Ha	Ma	Mo	La	Oa	Ka	W	C	L	
1966 May						Oa					
1966 June						Oa				L	
1966 Oct		Ha							C	L	
1967 Oct		Ha									
1967 Oct		Ha						W	C		
1967 Nov		Ha									
1968 Oct	1968 Nov	Ha						W			
1969 June			Ma								
1969 June		Ha						W			
1969 Oct		Ha	Ma	Mo	La	Oa	Ka	W		L	F
1970 Feb	1970 Apr	Ha						W	C	L	
1970 Feb	1970 Apr	Ha						W	C	L	F
1970 Mar						Oa					F
1971 June		Ha	Ma					W		L	
1971 June	1971 Aug	Ha								L	
1971 June	1971 Sep	Ha	Ma	Mo	La	Oa	Ka	W	C		
1971 Aug			Ma					W			
1971 Aug		Ha	Ma					W	C		

TABLE 23.—*Continued*

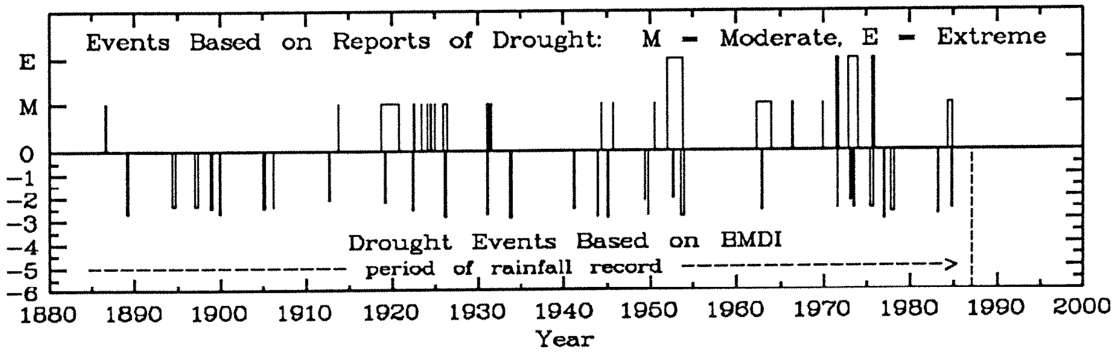
DROUGHT EVENTS From	To	ISLANDS AFFECTED*						IMPACT†			
1971 Sep			Ma					W	C		
1971 Dec			Ma	Mo				W		L	
1972 Jan			Ma								
1972 Mar		Ha									
1972 Mar		Ha									
1972 Mar		Ha									F
1972 Mar		Ha							C		
1972 June			Ma								
1972 June		Ha	Ma						C	L	
1972 Nov	1973 May	Ha									
1972 Dec			Ma						C		
1973 Jan		Ha	Ma	Mo	La	Oa	Ka	W		L	
1973 Jan		Ha									
1973 Jan	1973 Nov									L	F
1973 Feb							Ka				
1973 Feb		Ha							C		
1973 Feb		Ha				Oa			C		F
1973 Mar		Ha							C	L	F
1973 Apr		Ha							C	L	
1973 May		Ha									
1973 July		Ha									
1973 Aug			Ma								
1973 Sep			Ma								
1973 Nov							Ka				
1974 Feb		Ha								L	
1974 Mar	1974 Oct	Ha						W	C		
1974 Oct		Ha								L	
1975		Ha							C		
1975 Apr	1975 May						Ka				
1975 Aug		Ha							C		
1975 Sep	1975 Oct	Ha	Ma	Mo	La	Oa	Ka		C		
1975 Sep	1975 Nov						Ka	W	C	L	
1976 Dec						Oa					
1976 Dec						Oa					
1976 Dec		Ha									
1976 Dec		Ha									
1977		Ha	Ma	Mo	La	Oa	Ka				
1977		Ha	Ma								
1977 Jan		Ha	Ma								
1977 Jan	1977 Feb	Ha	Ma			Oa					
1977 Feb		Ha						W	C	L	
1977 Mar		Ha									
1978 Jan		Ha									
1978 Jan		Ha									
1978 Feb										L	
1978 Feb		Ha	Ma						C	L	
1978 Mar		Ha									
1978 Apr		Ha	Ma								
1980 Jan	1980 Feb	Ha									
1980 Oct		Ha								L	
1980 Nov	1980 Dec	Ha									
1980 Nov	1980 Dec	Ha						W	C	L	
1981		Ha	Ma								
1981 Jan			Ma					W			
1981 Jan		Ha						W	C	L	
1981 Jan	1981 Feb	Ha						W	C	L	
1981 Mar		Ha									F
1981 Apr		Ha						W	C		
1981 May		Ha									F
1981 June			Ma								F
1981 June			Ma					W	C		
1981 June		Ha							C	L	F
1981 June		Ha						W			
1981 July						Oa		W			
1981 July			Ma								F
1981 July		Ha						W			
1981 July		Ha						W			
1981 Aug		Ha							C	L	

TABLE 23.—*Continued*

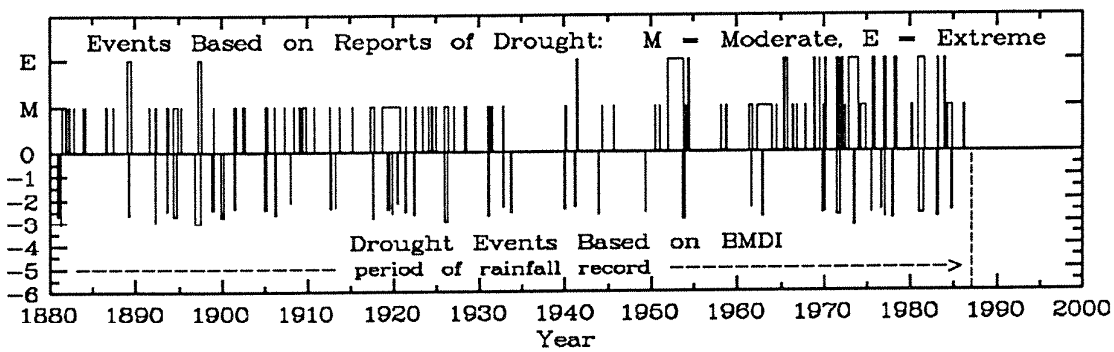
DROUGHT EVENTS From	To	ISLANDS AFFECTED*						IMPACT†				DROUGHT EVENTS From	To	ISLANDS AFFECTED*						IMPACT†			
1983 Feb		Ha									F	1984 Mar		Ha	Ma	Mo	La	Oa	Ka				
1983 Feb		Ha						W			F	1984 Apr						Oa		W			
1983 Feb		Ha						W	C	L		1984 June		Ha					Ka				
1983 Mar			Ma					W				1984 July											
1983 Mar		Ha						W				1984 July		Ha	Ma	Mo	La	Oa	Ka	W	C	L	
1983 Mar		Ha						W			F	1984 July		Ha								L	
1983 Mar		Ha						W	C			1984 July	1984 Aug					Oa		W			
1983 Mar		Ha	Ma					W				1984 Aug			Ma					W			
1983 Nov		Ha								L		1984 Oct		Ha	Ma			Oa		W	C	L	F
1983 Dec						Oa						1986 Feb		Ha						W	C	L	
1983 Dec			Ma								F	1986 Mar			Ma			Oa	Ka	W	C		
1983 Dec		Ha																					

*Islands: Ha = Hawai'i, Ma = Maui, Mo = Moloka'i, La = Lāna'i, Oa = O'ahu, Ka = Kaua'i.
†W = water supply, C = crop, L = livestock, F = fire.

HAWAI'I STATE



HAWAI'I



MAUI

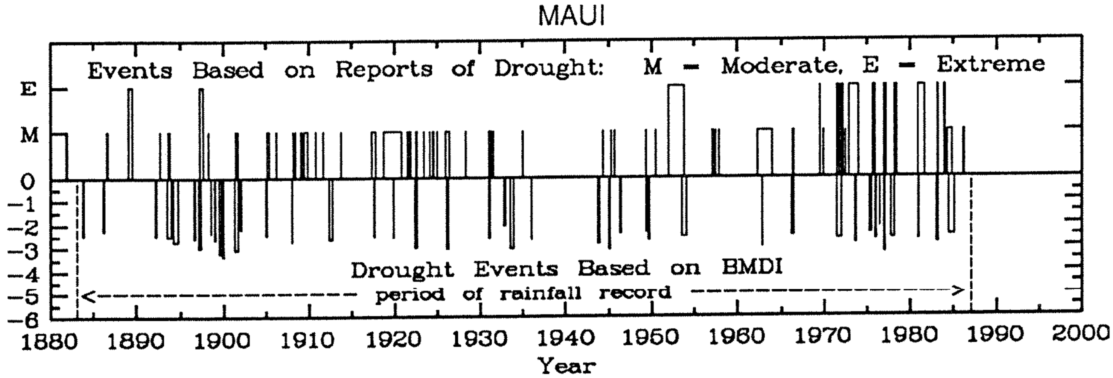
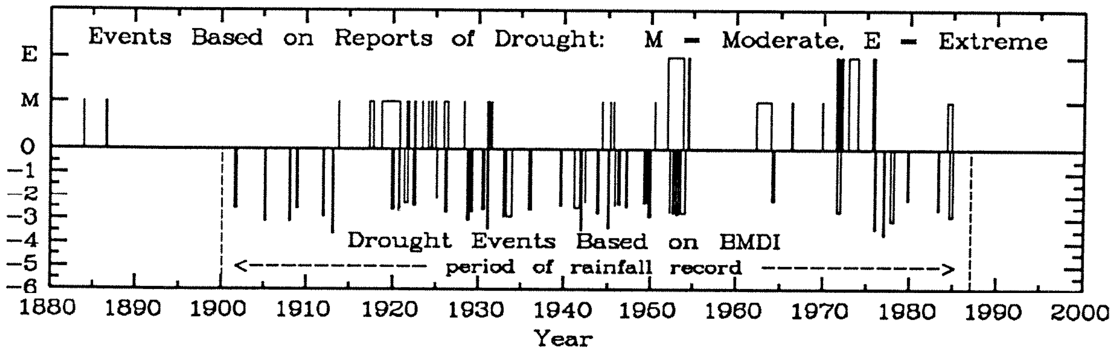
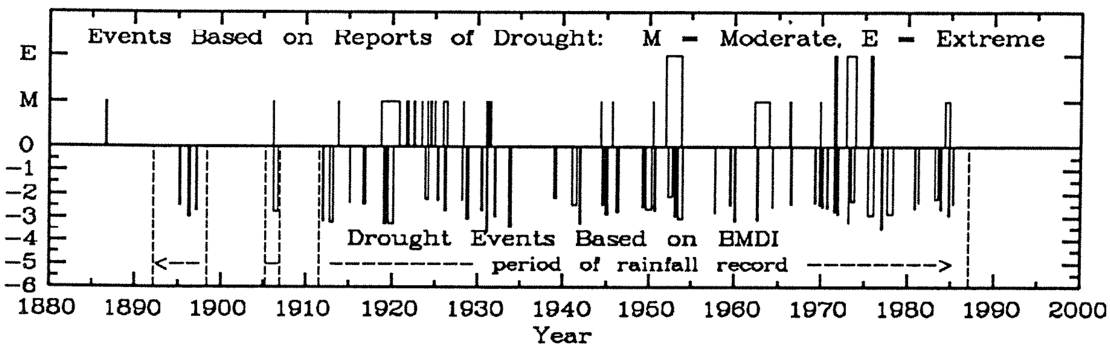


Figure 43. Comparison of drought events based on reports vs. events based on BMDI for Hawai'i State and six major islands

MOLOKA'I



LĀNA'I



O'AHU

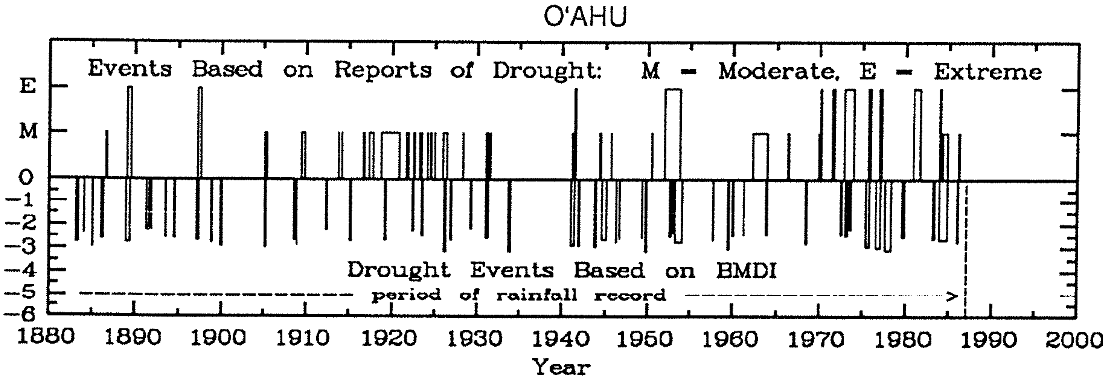


Figure 43.—*Continued*

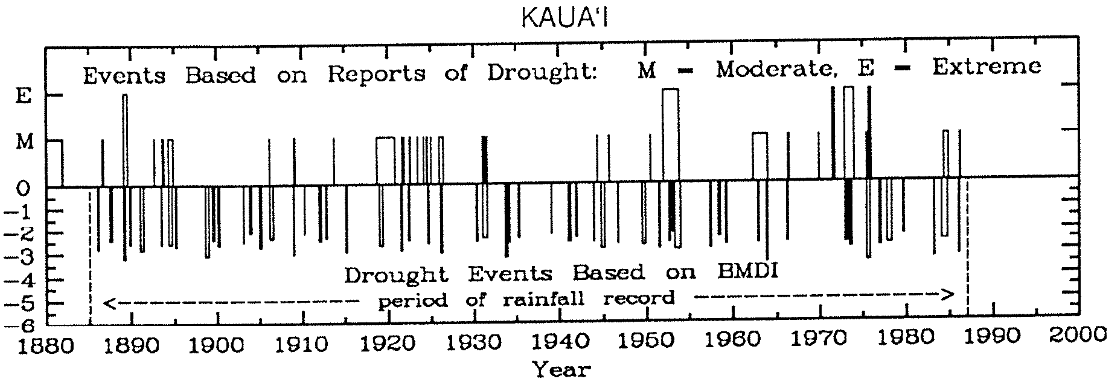


Figure 43.—*Continued*

found. Second, no assurance exists that drought reporting is complete. An event of a given severity may receive detailed newspaper coverage while an equally severe drought may not be reported. Third, drought impacts, on which drought reports are based, change as economic activities, population, and drought mitigation technology change. On the one hand, population growth and the associated greater demand for water would generally lead to greater drought impacts. On the other hand, development of water supply systems based on groundwater would tend to reduce these impacts. It would be difficult to sort out the combined effects on drought reporting of these changes and the decreasing dependency on agriculture.

ENVIRONMENTAL IMPACTS OF DROUGHT

Air Temperature

Droughts are usually thought of as periods of hot as well as dry weather. It is reasonable to expect the two conditions to be correlated because (1) dry weather usually means clear skies and, hence, higher insolation; and (2) dry conditions mean energy normally used to evaporate water from moist soil and vegetation is instead used to heat the surface and the air. To investigate the extent to which droughts in Hawai'i are accompanied by warmer air, we analyzed daily temperature maximums. Daily maxima correspond to daytime temperatures when the warming influence of dry weather would presumably be greatest. Mean maximum air temperatures for each month beginning in 1949 were obtained from National Weather Service records. Time series plots of these values reveal significant upward temperature trends at most stations due to the increasing urbanization of the islands. The trends appear to be linear at most stations. Anomalies were calculated as departures from the linear trend line obtained using least squares regression. For each rainfall network station for which temperature data were available, cumulative temperature anomalies were calculated for each station drought event by adding each monthly temperature departure during a given event. Results are given in Tables 24 through 31. Only droughts for which temperature data were available are listed. The tables show that droughts are predominantly periods of anomalously high daytime air temperature, although numerous exceptions are indicated. The most notable positive anomalies were at Station 73.2 on Hawai'i Island during the August to September 1950 drought, averaging 5.5 degrees above normal, and the December 1985 to May 1986 event, averaging 4.7 degrees warmer than normal. Station 847 on O'ahu is exceptional for having a majority of its droughts associated with negative air temperature anomalies.

Streamflow

In many areas of the state, streamflow is developed for irrigation and drinking water. Limited amounts are also used for cooling power plants, and some streams are harnessed for hydroelectric generation. On Maui, water diverted from streams draining the wet northern and northeastern slopes of Haleakalā has long been used to irrigate sugarcane. The growing residential population of the area known as "Upcountry Maui" including Makawao, Pukalani, and Kula, are also increasingly dependent on surface water diversion for drinking water. During periods of drought, streamflow is reduced and water diverted by ditches into reservoirs is diminished, bringing severe water shortage to areas supplied by surface water systems. To illustrate the response of streamflow to drought, Figures 44 and 45 shows the monthly BMDI for Station 442 (Lupi Upper), and mean monthly discharge of Waikamoi Stream from 1922 through 1956. The correspondence between the rainfall record, reflected in the drought index, and the stream discharge is apparent throughout the record. Low flows are invariably associated with low BMDI values. The droughts of 1922, 1925–1926, 1933, 1935–1936, 1943–1944, and 1953 are good examples. Because of the small size of Hawaiian watersheds, the rise and fall of stream hydrographs follow rainfall fluctuations with very little lag so that hydrologic droughts tend to be almost simultaneous with meteorological drought. According to Figures 44 and 45, the frequency and duration of hydrologic droughts are also very similar to those of meteorological drought.

Soil Moisture

Most agricultural crops as well as natural vegetation must meet the environmental demand for evaporation by obtaining water from the soil. Prolonged periods of deficient soil moisture will lead to reduced growth and, ultimately, the death of plants. Crop yields are very strongly related to water availability. While much of the cultivated area of the islands is irrigated and, thus, somewhat less vulnerable to short-term drought, many areas of rain-fed cultivation,

TABLE 24. CUMULATIVE AIR TEMPERATURE ANOMALIES DURING DROUGHT EVENTS CALCULATED ON BASIS OF MONTHLY AVERAGES OF DAILY MAXIMA AT NAALEHU, HAWAI'I (STA. 14)

DROUGHT EVENTS*					SEVERITY	MAGNITUDE	DURATION	CUM. TEMP. ANOMALY
Rank	Period							
	From		To				(mo)	(°C)
5	1980	Oct	1981	June	-21.72	-2.41	9	8.49
6	1972	Nov	1973	Apr	-19.15	-3.19	3	-1.44
9	1984	Feb	1984	June	-15.95	-3.19	5	4.29
10	1977	Oct	1978	Feb	-15.37	-3.07	3	-1.43
11	1975	May	1975	Oct	-15.26	-2.54	4	0.31
15	1983	July	1983	Nov	-12.38	-2.48	5	-1.82
16	1954	Apr	1954	July	-12.33	-3.08	0	0.00
17	1969	Dec	1970	Mar	-12.08	-3.02	4	5.30
20	1983	Jan	1983	Apr	-11.71	-2.93	4	1.99
21	1962	Nov	1963	Feb	-10.86	-2.72	4	4.18
24	1985	May	1985	Aug	-9.90	-2.48	4	-0.79
25	1986	Jan	1986	Mar	-9.74	-3.25	3	5.24

*Includes only those events for which temperature data were available.

TABLE 25. CUMULATIVE AIR TEMPERATURE ANOMALIES DURING DROUGHT EVENTS CALCULATED ON BASIS OF MONTHLY AVERAGES OF DAILY MAXIMA AT HAWAI'I VOLCANOES NATIONAL PARK HEADQUARTERS, HAWAI'I (STA. 54)

DROUGHT EVENTS*					SEVERITY	MAGNITUDE	DURATION	CUM. TEMP. ANOMALY
Rank	Period							
	From		To				(mo)	(°C)
4	1949	Apr	1949	Sep	-20.28	-3.38	0	0.00
7	1979	Aug	1980	Feb	-19.48	-2.78	7	9.21
8	1969	Oct	1970	Mar	-18.65	-3.11	6	1.27
9	1976	July	1977	Jan	-16.66	-2.38	7	-2.74
10	1977	Nov	1978	Mar	-15.64	-3.13	5	3.60
13	1961	Apr	1961	Sep	-14.68	-2.45	6	0.99
14	1953	July	1953	Nov	-14.42	-2.88	5	1.01
15	1962	Oct	1963	Feb	-14.14	-2.83	5	2.03
17	1983	Jan	1983	Apr	-13.36	-3.34	4	6.43
18	1985	Dec	1986	Mar	-12.62	-3.15	4	6.54
22	1975	June	1975	Sep	-10.22	-2.56	4	-5.75
27	1984	Sep	1984	Oct	-7.12	-3.56	2	2.26

*Includes only those events for which temperature data were available.

TABLE 26. CUMULATIVE AIR TEMPERATURE ANOMALIES DURING DROUGHT EVENTS CALCULATED ON BASIS OF MONTHLY AVERAGES OF DAILY MAXIMA AT KAINALIU, HAWAI'I (STA. 73.2)

DROUGHT EVENTS*					SEVERITY	MAGNITUDE	DURATION	CUM. TEMP. ANOMALY
Rank	Period							
	From		To				(mo)	(°C)
1	1977	June	1978	Mar	-41.83	-4.18	10	20.74
2	1973	Feb	1973	Sep	-39.66	-4.96	8	-12.35
3	1970	Mar	1970	Oct	-27.36	-3.42	8	0.53
4	1966	Apr	1966	Sep	-20.63	-3.44	6	1.53
5	1958	Jan	1958	July	-19.54	-2.79	7	-0.17
6	1983	Jan	1983	May	-19.04	-3.81	5	-5.88
8	1976	Sep	1977	Feb	-17.80	-2.97	6	2.01
9	1969	Mar	1969	July	-14.69	-2.94	5	2.21
10	1985	Dec	1986	May	-14.58	-2.43	4	18.74
13	1985	Apr	1985	June	-9.70	-3.23	2	1.16
14	1971	May	1971	June	-9.60	-4.80	2	-0.65
16	1981	Sep	1981	Oct	-8.80	-4.40	2	6.10
18	1982	July	1982	Sep	-7.07	-2.36	3	5.72
19	1972	Apr	1972	June	-7.05	-2.35	3	-3.49
20	1984	Feb	1984	Mar	-6.82	-3.41	2	4.61
22	1983	Oct	1983	Nov	-6.45	-3.22	2	0.97
23	1984	Aug	1984	Sep	-6.44	-3.22	2	-6.12
24	1950	Aug	1950	Sep	-5.94	-2.97	2	11.05
25	1959	Sep	1959	Oct	-5.42	-2.71	2	1.43
26	1969	Oct	1969	Nov	-5.35	-2.67	2	-0.85
27	1957	Sep	1957	Oct	-5.18	-2.59	2	4.77

*Includes only those events for which temperature data were available.

TABLE 27. CUMULATIVE AIR TEMPERATURE ANOMALIES DURING DROUGHT EVENTS CALCULATED ON BASIS OF MONTHLY AVERAGES OF DAILY MAXIMA AT KOHALA MISSION, HAWAI'I (STA. 175.1)

DROUGHT EVENTS*					SEVERITY	MAGNITUDE	DURATION	CUM. TEMP. ANOMALY
Rank	Period							
	From		To				(mo)	(°C)
4	1971	May	1972	Jan	-25.79	-2.87	9	-1.73
10	1962	June	1962	Dec	-19.00	-2.71	7	2.12
13	1965	Apr	1965	Oct	-17.13	-2.45	7	9.61
14	1974	May	1974	Sep	-16.42	-3.28	5	3.94
19	1961	July	1961	Oct	-13.86	-3.47	4	4.32
20	1951	Apr	1951	July	-13.15	-3.29	4	3.27
23	1953	Jan	1953	Apr	-12.28	-3.07	4	2.98
24	1972	May	1972	Aug	-12.26	-3.07	4	0.83
26	1954	Jan	1954	Apr	-11.71	-2.93	4	2.81

*Includes only those events for which temperature data were available.

TABLE 28. CUMULATIVE AIR TEMPERATURE ANOMALIES DURING DROUGHT EVENTS CALCULATED ON BASIS OF MONTHLY AVERAGES OF DAILY MAXIMA AT ʻEWA MILL, OʻAHU (STA. 741)

DROUGHT EVENTS*					SEVERITY	MAGNITUDE	DURATION (mo)	CUM. TEMP. ANOMALY (°C)
Rank	Period							
	From		To					
1	1976	May	1977	Mar	-29.74	-2.70	5	4.35
8	1952	Mar	1952	Sep	-16.64	-2.38	7	-3.29
15	1975	May	1975	Oct	-14.52	-2.42	5	-1.37
21	1953	May	1953	Sep	-13.37	-2.67	5	0.65
22	1970	Feb	1970	June	-13.16	-2.63	5	-0.42
29	1959	Mar	1959	June	-8.87	-2.22	4	3.15
30	1949	Sep	1949	Nov	-8.54	-2.85	2	-1.16
37	1973	Jan	1973	Mar	-7.84	-2.61	2	-0.46
38	1959	Dec	1960	Feb	-7.74	-2.58	3	-0.08

*Includes only those events for which temperature data were available.

TABLE 29. CUMULATIVE AIR TEMPERATURE ANOMALIES DURING DROUGHT EVENTS CALCULATED ON BASIS OF MONTHLY AVERAGES OF DAILY MAXIMA AT WAIALUA, OʻAHU (STA. 847)

DROUGHT EVENTS*					SEVERITY	MAGNITUDE	DURATION (mo)	CUM. TEMP. ANOMALY (°C)
Rank	Period							
	From		To					
2	1953	May	1953	Dec	-26.41	-3.30	8	-0.83
4	1973	Jan	1973	Sep	-22.81	-2.53	9	-5.05
6	1975	Apr	1975	Oct	-21.78	-3.11	7	-3.52
7	1977	Aug	1978	Feb	-18.34	-2.62	7	3.56
9	1957	May	1957	Oct	-15.74	-2.62	6	-0.80
11	1952	Apr	1952	Sep	-15.50	-2.58	6	-5.05
13	1983	Nov	1984	Mar	-14.80	-2.96	3	2.87
16	1959	Mar	1959	July	-12.80	-2.56	5	1.18
17	1949	Aug	1949	Nov	-12.58	-3.14	3	-1.06
21	1970	Mar	1970	June	-10.56	-2.64	4	2.85
22	1976	Dec	1977	Feb	-10.44	-3.48	3	2.66
23	1951	June	1951	Sep	-10.40	-2.60	4	1.61
30	1984	Aug	1984	Oct	-8.20	-2.73	3	-0.54
31	1959	Dec	1960	Jan	-7.47	-3.74	2	-0.47
34	1976	June	1976	Aug	-7.20	-2.40	3	-2.27
36	1952	Dec	1953	Jan	-6.81	-3.40	2	2.35

*Includes only those events for which temperature data were available.

TABLE 30. CUMULATIVE AIR TEMPERATURE ANOMALIES DURING DROUGHT EVENTS CALCULATED ON BASIS OF MONTHLY AVERAGES OF DAILY MAXIMA AT KAHUKU, O'AHU (STA. 912)

DROUGHT EVENTS*								CUM. TEMP.
Rank	Period				SEVERITY	MAGNITUDE	DURATION	ANOMALY
	From		To				(mo)	(°C)
7	1953	June	1953	Dec	-20.19	-2.88	7	0.44
23	1971	July	1971	Nov	-10.56	-2.11	2	-0.04
25	1972	Dec	1973	Mar	-10.07	-2.52	2	0.43
34	1959	May	1959	July	-6.90	-2.30	3	1.44
38	1949	Oct	1949	Nov	-6.10	-3.05	2	1.41
39	1951	June	1951	July	-6.08	-3.04	2	0.75

*Includes only those events for which temperature data were available.

TABLE 31. CUMULATIVE AIR TEMPERATURE ANOMALIES DURING DROUGHT EVENTS CALCULATED ON BASIS OF MONTHLY AVERAGES OF DAILY MAXIMA AT MANA, KAUA'I (STA. 1026)

DROUGHT EVENTS*								CUM. TEMP.
Rank	Period				SEVERITY	MAGNITUDE	DURATION	ANOMALY
	From		To				(mo)	(°C)
1	1952	Dec	1953	Nov	-27.32	-2.28	12	-1.40
2	1973	Jan	1973	Oct	-26.84	-2.68	10	-3.84
8	1957	Apr	1957	Oct	-16.71	-2.39	7	3.23
10	1976	Oct	1977	Feb	-13.37	-2.67	5	1.76
14	1975	June	1975	Oct	-12.16	-2.43	5	-3.40
20	1955	Apr	1955	July	-9.56	-2.39	2	-1.77
23	1949	Sep	1949	Nov	-8.78	-2.93	2	0.56
24	1963	Oct	1963	Dec	-8.56	-2.85	3	0.58
25	1952	Apr	1952	June	-7.78	-2.59	3	-0.72
28	1960	July	1960	Sep	-6.75	-2.25	3	-1.07
32	1977	Oct	1977	Nov	-5.62	-2.81	2	1.16
34	1969	Sep	1969	Oct	-5.38	-2.69	2	0.44
37	1958	May	1958	June	-5.32	-2.66	2	0.66
41	1970	Mar	1970	Apr	-5.10	-2.55	2	2.60
42	1961	Feb	1961	Mar	-5.06	-2.53	2	1.45
43	1966	May	1966	June	-4.97	-2.49	2	2.50
44	1978	Feb	1978	Mar	-4.96	-2.48	2	0.01

*Includes only those events for which temperature data were available.

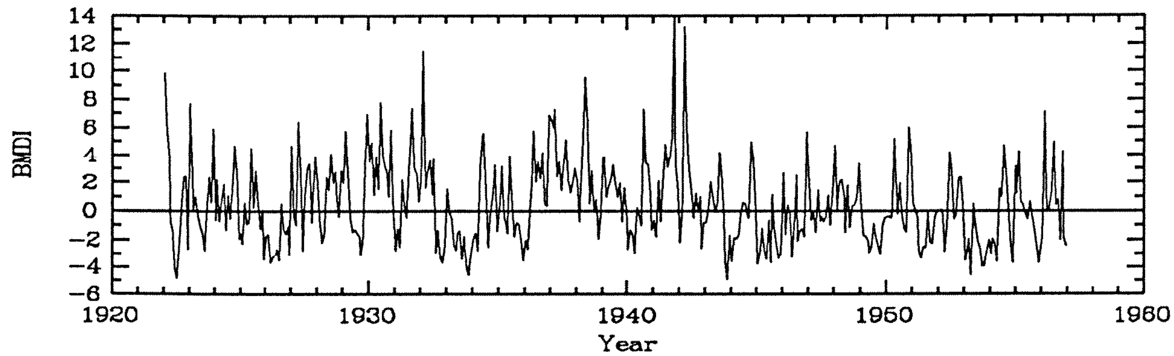


Figure 44. Monthly BMDI at Lupi Upper, Maui Island (Sta. 442), 1922–1956

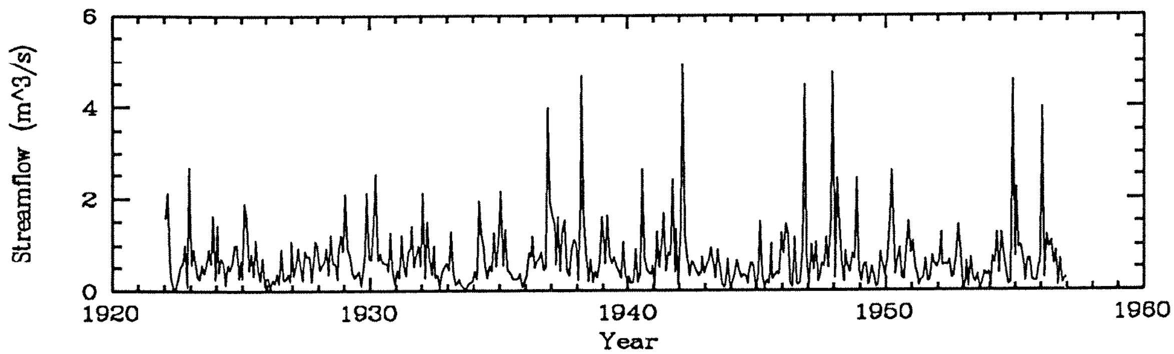


Figure 45. Monthly streamflow time series for Waikamoi Stream above Wailoa Ditch, Maui Island, 1922–1956

pastures, and forests are strongly impacted by periods of inadequate soil moisture resulting from low rainfall. To examine the relationship between meteorological drought and agricultural drought, Figures 46 and 47 shows the time series of monthly BMDI at Station 863 (Wahiawa Dam) on O'ahu, and the monthly soil moisture storage for a site along the windward slopes of the Wai'anae mountains from 1946 through 1975. Soil moisture was calculated using a water-balance model (Giambelluca 1983*a,b*). Values of soil moisture are given as percentages of the water holding capacity of the soil. This provides an absolute index, unadjusted for the mean annual cycle. Thus, the pronounced annual rainfall cycle in the region is readily apparent in the graph. Comparison with the BMDI is somewhat difficult since the index is derived relative to monthly means, effectively removing the annual cycle from the time series. Winter droughts, such as the 1953, 1960, 1964, and 1973 events, result in failure of soil moisture to rise above the 50% level during the wet season. Droughts during the dry season tend to reduce soil moisture levels to extremely low levels of less than 10%, during the late summer or early autumn. Examples are in 1946, 1949, 1957, 1968, and 1975.

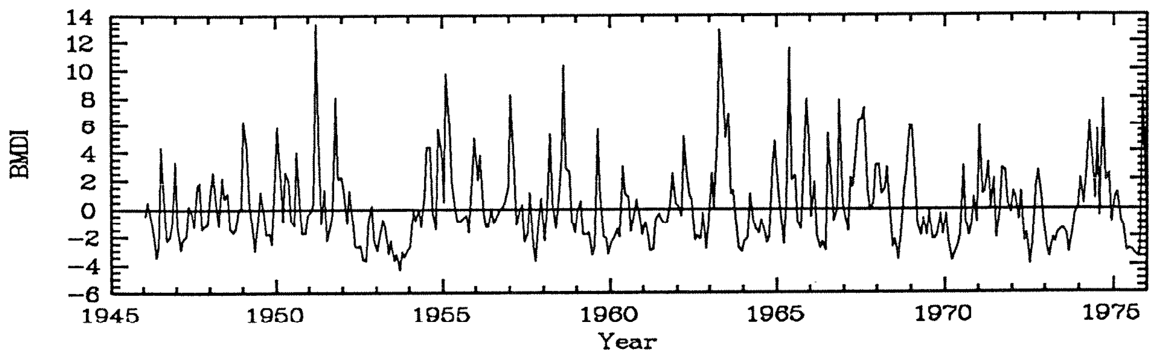


Figure 46. Monthly BMDI at Wahiawa Dam, O'ahu Island (Sta. 863), 1946–1975

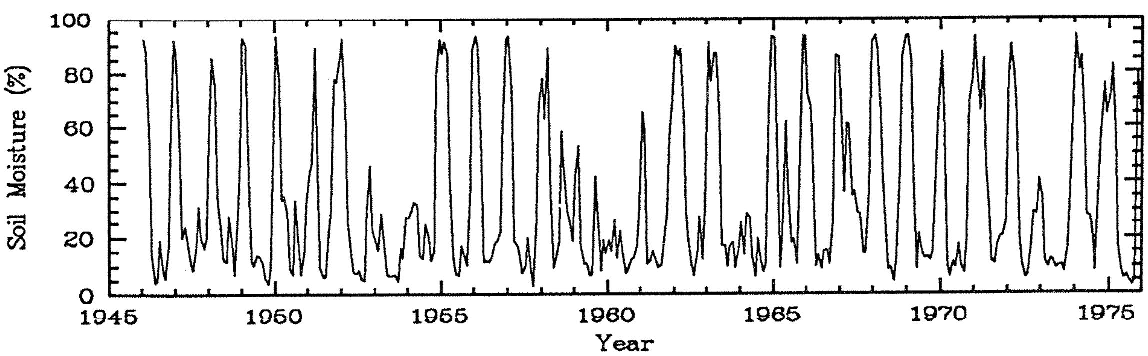


Figure 47. Soil moisture storage, Windward Wai'anae slopes, O'ahu Island, 1946–1975

Groundwater

The most important aquifers in Hawai'i contain lenses of fresh water floating on more dense seawater. In accordance with the principles of Badon Ghyben (1888) and Herzberg (1901), and elaborated by Hubbert (1969), such lenses of fresh water extend 40 m below sea level for every meter of water level above sea level. Near the bottom of the lens, freshwater grades through a zone of transition, eventually to reach the chloride concentration of seawater, 19,000 mg/l. Wentworth (1951), Essaid (1986), Eyre, Ewart, and Shade (1986), and Eyre (1987) suggest that the thickness of the freshwater lens is best predicted by water levels averaged over several years. They show that daily or seasonal fluctuations in the water table of up to several feet do not result in a corresponding motion of 40 times that amount at the bottom of the freshwater lens.

The flow of groundwater through these aquifers is sustained by the deep percolation of rainfall. The elevation of the water table and subsequent thickness of the freshwater lens is determined by the "Ghyben-Herzberg ratio" of 40:1, by the flow rate (recharge rate) of groundwater in the aquifer, the hydraulic conductivity of the aquifer, and the ease with which the groundwater can escape from the aquifer and discharge into the ocean.

Of ultimate concern is the potability of the pumped water, which is frequently affected by high chloride concentration. An understanding, and quantification to the extent possible, of the causes of high chloride concentration in pumped water would allow water well operators to better manage their aquifers and pumping systems. Such an understanding would include a knowledge of the relative importance of well depth and pumping rate, groundwater flow rates, size of the aquifer, and variations in rainfall and recharge.

Focus on the yearly variations in rainfall leads directly to an investigation of droughts and their effect on the size of the freshwater lens. A key parameter affecting an aquifer's resilience to drought is the residence time (the ratio of storage capacity to average flow rate) of groundwater in the aquifer. A range of examples illustrates the importance of residence time. A typical rainwater catchment for a household may hold 20 m^3 (5,000 gal). With average use of 0.4 m^3 (100 gal)/day, the residence time in the tank is 50 days. A 2-month drought duration will have severe impact on the water supply of the household. The Laura area of the Pacific atoll of Majuro has a freshwater lens that averages storage of approximately 2 million m^3 (500 million gal) of freshwater, recharged at a rate of 0.1 m^3/s (2 mgd) by rainfall. Residence time in this freshwater lens is about 7 or 8 months. Because of this relatively short residence time, the size of the lens fluctuates in response to the annual rainfall cycle and to individual storm events. An extended drought would cause the lens to shrink substantially and threaten the potability of well water. On the other hand, the Pearl Harbor aquifer on O'ahu is less sensitive to periods of low rainfall. Flow through the aquifer and storage are approximately 9 m^3/s (200 mgd) and 3 billion m^3 (750 billion gal), respectively. The residence time of the Pearl Harbor aquifer is about 10 years.

Individual droughts in Hawai'i last from 2–13 months and reduced recharge during these events is not expected to have a significant effect on the thickness of a freshwater lens whose residence time is several years. However, when several consecutive droughts of long duration are separated by relatively short periods of normal rainfall, the water table will decline as a result of lower recharge, the lens may become thinner, and, as a result, the chloride concentration of pumped water may increase.

To investigate the effects of drought on the quality of Hawaiian groundwater, a system with a thick freshwater lens, the Pearl Harbor aquifer, and a thin-lens system, the Kona aquifer near Keauhou, were examined. The Pearl Harbor aquifer contains a lens of fresh water floating on seawater. The freshwater thickness, flow rate through the aquifer, storage, and residence times of the aquifers are respectively 250 m (800 ft), 9 m^3/s (200 mgd), 3 billion m^3

(750 bil gal), and 10 years for the Pearl Harbor aquifer, and 45 m (150 ft), 4.4 m^3/s (100 mgd), 1.1 billion m^3 (300 bil gal), and 8 years for the Kona aquifer.

PEARL HARBOR AQUIFER. To determine the relative importance of drought conditions versus pumping rate on the size of the freshwater lens in the Pearl Harbor aquifer, the rainfall , drought index, recharge, groundwater level, and pumping rate are analyzed. Specifically, we examine monthly rainfall at 'Ewa Mill (Station 741) from 1950 to 1975 (Fig. 48), the corresponding monthly BMDI at Station 741 (Fig. 49), Pearl Harbor basin annual groundwater recharge (Giambelluca 1983*a*) (Fig. 50), monthly water level for Well 2300-10 in the Pearl Harbor basin (Fig. 51), Pearl Harbor basin monthly pumpage rate (Fig. 52), and Pearl Harbor basin annual pumpage rate (Fig. 53). The annual cycle in rainfall, pumpage, and water level is evident. Months of peak pumping correspond with the dry summer months and minimum water levels. Also evident is the overall increase in annual pumpage beginning in the late 1950s, and the corresponding decline in water level. The rainfall record and drought index show variations about a stable mean with no trends to correspond with the declining water levels.

The relationships among rainfall, water levels, and pumpage are best investigated with the use of a groundwater flow model. Souza and Voss (1987), using the density-dependent flow and transport model SUTRA on a vertical cross-section of the Pearl Harbor aquifer, produced the simulated water level time series shown in Figure 54. It is noteworthy that generally close agreement (within 0.4 m) between simulated and observed water levels was achieved using a constant recharge rate and varying only the pumpage based on the monthly record shown in Figure 52. However, there are periods when the simulated water levels are consistently above or below measured levels. The actual recharge time series was not constant over this time period, as assumed in the model, but fluctuated above and below the average in concert with the rainfall. When extended periods of over- or under-prediction of water levels are compared with the drought index, it is evident that the prediction errors are negatively correlated with deviation of rainfall from the mean, that is, the model (using constant recharge rate) overestimates water levels during dry periods and underestimates water levels during wet periods (Table 32). The comparison shows that a lag of one to two years occurs between wet or dry periods and the corresponding periods of under or over prediction of water levels, consistent with Eyre's (1987) observations.

Although noticeable, the direct effect of rainfall variations on fluctuations in the water table is slight. Pumpage, on the other hand, has a far greater and more immediate impact on water levels. The effect of dry periods in the Pearl Harbor basin is to increase both agricultural and domestic water demand, resulting in higher pumpage, which in turn causes water levels to decline.

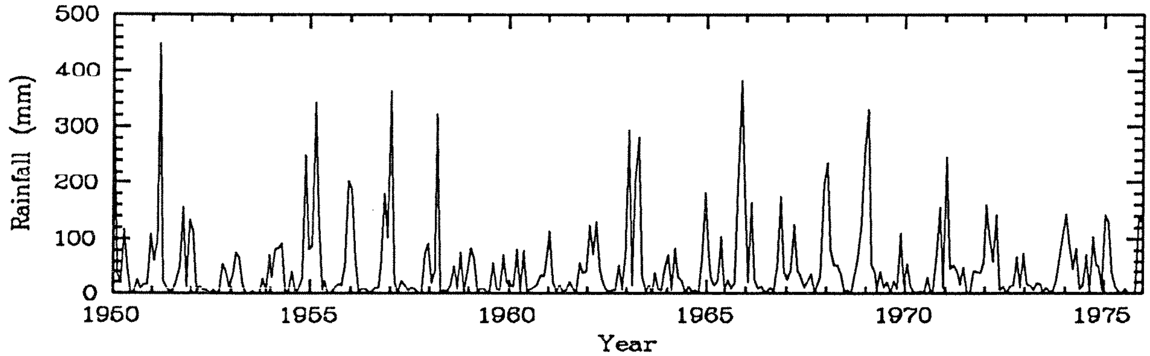


Figure 48. Monthly rainfall at ‘Ewa Mill, O‘ahu Island (Sta. 741), 1950–1975

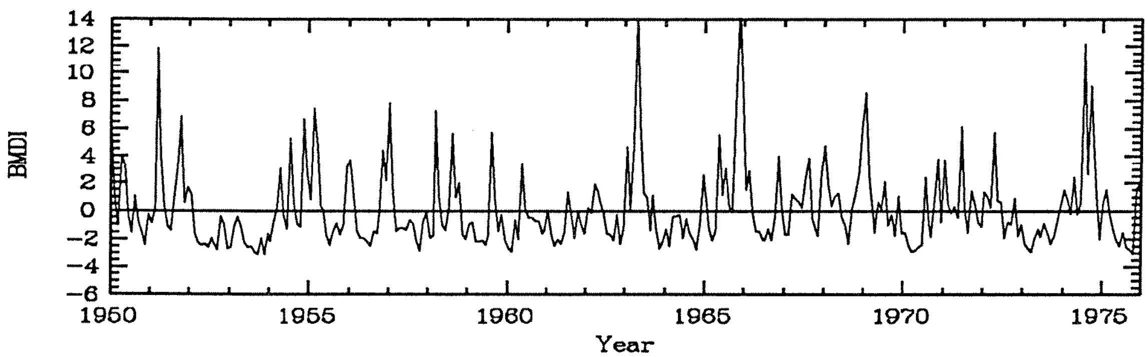
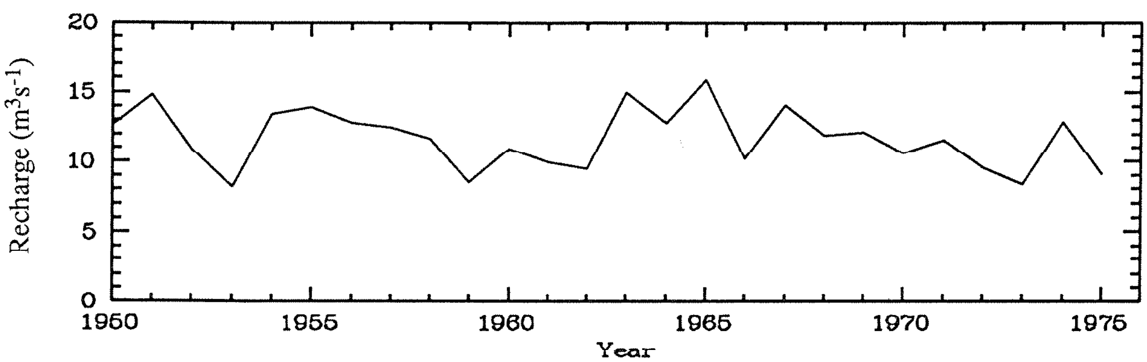


Figure 49. Monthly BMDI at ‘Ewa Mill, O‘ahu Island (Sta. 741), 1950–1975



SOURCE: Giambelluca (1983*a*).

Figure 50. Annual recharge, Pearl Harbor Basin, O‘ahu Island, 1950–1975

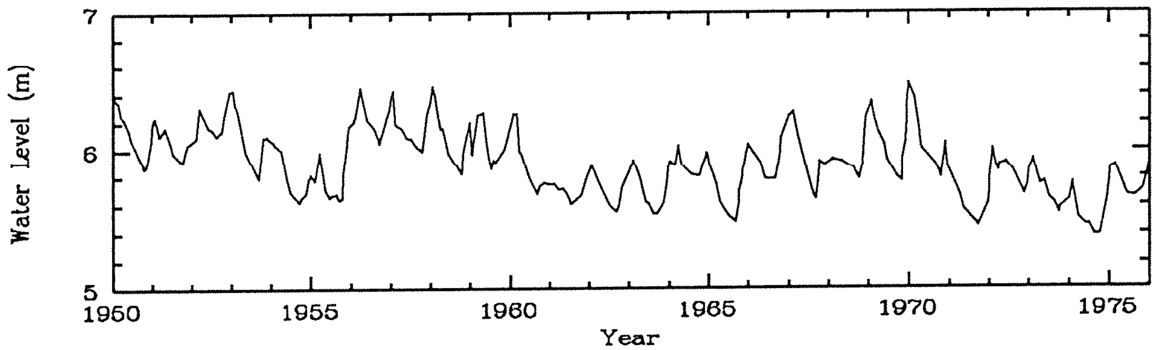


Figure 51. Monthly water level for Well 2300-10, Pearl Harbor Basin, O'ahu Island, 1950–1975

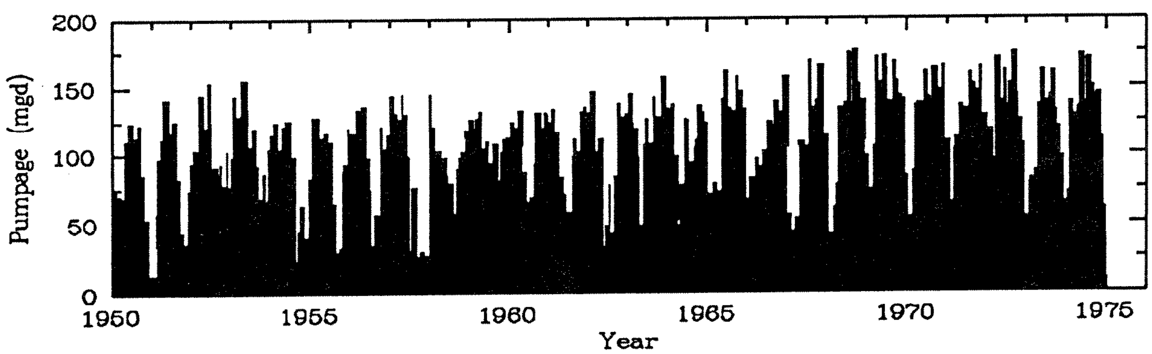


Figure 52. Monthly pumpage, Pearl Harbor Basin, O'ahu Island, 1950–1975

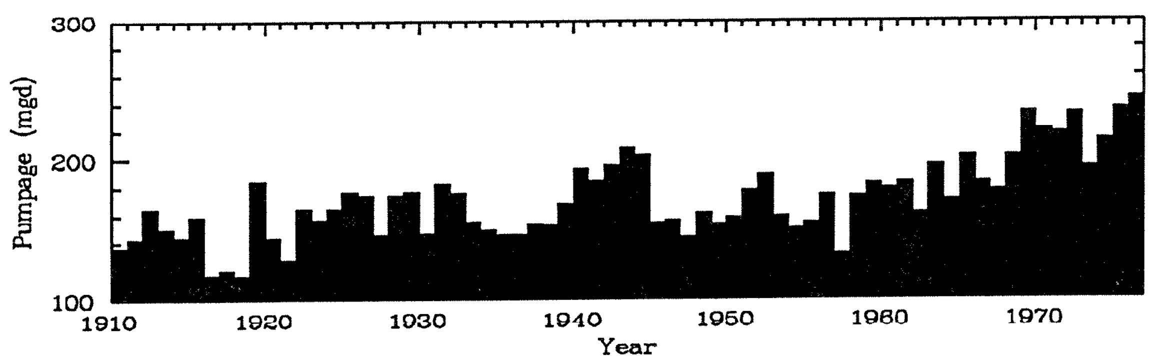
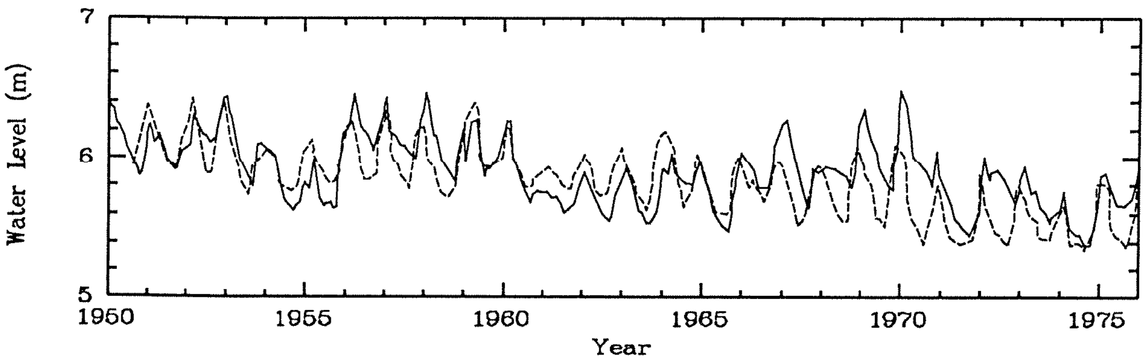


Figure 53. Annual pumpage, Pearl Harbor Basin, O'ahu Island, 1950–1975



SOURCE: Souza and Voss (1987).

Figure 54. Measured (solid line) and simulated water level, Pearl Harbor, O'ahu Island (Well 2300-10)

TABLE 32. WET AND DRY PERIODS VS. RESIDUAL BETWEEN SIMULATED AND OBSERVED WATER LEVELS, PEARL HARBOR AQUIFER, 1950–1975

Rainfall		Water Level Residuals	
1954–1958	Wet	1956–1958	OBS > Simulated
		1959–1961	OBS = Simulated
1959–1961	Dry	1961–1963	OBS < Simulated
1962–1964	Up and Down	1963–1965	OBS = Simulated
1965–1972	Wet	1966–1972	OBS > Simulated

Data from the Schofield high-level aquifer system supports this conclusion. In the Schofield aquifer the pumping rate is relatively small (approximately 0.2 m^3/s [4 mgd]) compared to the rate of groundwater recharge (approximately 8 m^3/s [180 mgd]) and does not mask the relationship between rainfall and water level. The monthly rainfall and water level record is shown in Figures 55–57. Note that large fluctuations in monthly rainfall (Fig. 55) are not matched in the water levels (Fig. 57), but that long-period fluctuations spanning several years, seen clearly in the 13-months moving average of rainfall (Fig. 56), are reflected the water levels. Note also that, as in Table 32, a lag of about 1 year separates extremes in the smoothed rainfall from extremes in water level. In a time series analysis, the cross correlation between these data is highest ($r = 0.76$) when water levels of successive months are correlated with the smoothed rainfall data from 14 months earlier (Eyre 1987).

If fluctuations in rainfall have little direct effect on water levels, then it must be inferred that rainfall fluctuations have little direct effect on the chloride concentration of water pumped from a large aquifer. Indeed, an examination of the records of chloride concentration from many

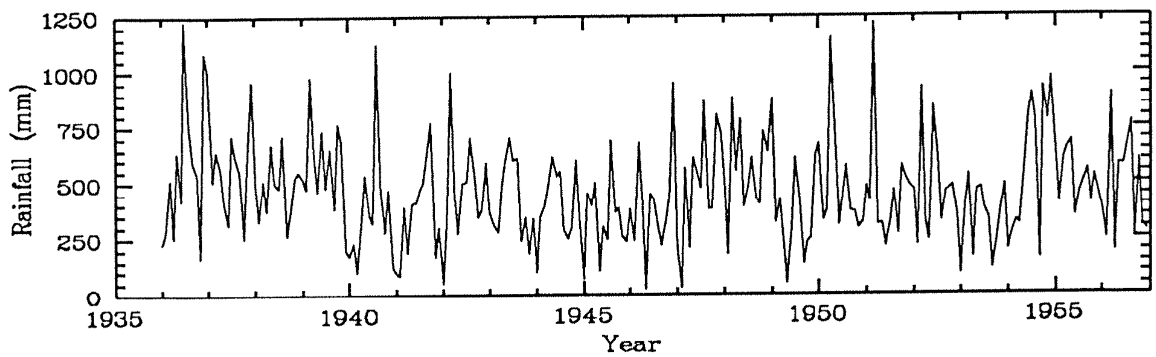


Figure 55. Monthly rainfall at Wahiawa Mauka near Ko'olau crest, O'ahu Island (Sta. 882), 1937–1956

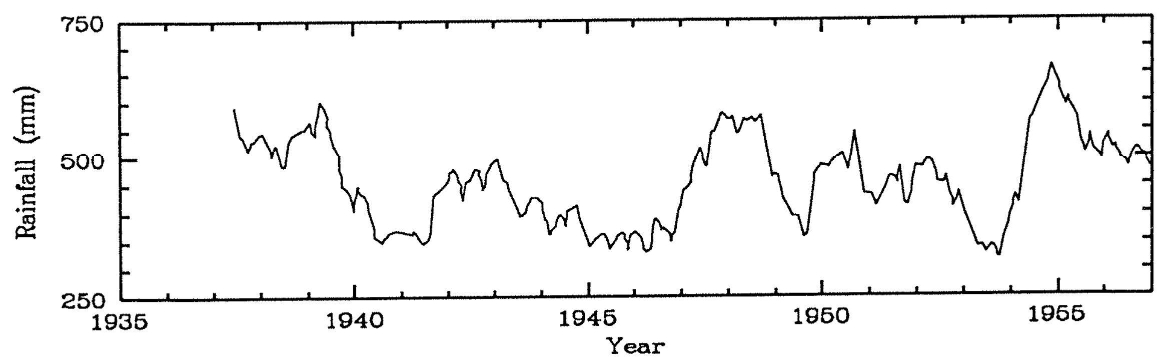


Figure 56. Center-weighted moving average of monthly rainfall at Wahiawa Mauka, O'ahu Island (Sta. 882), 1937–1956

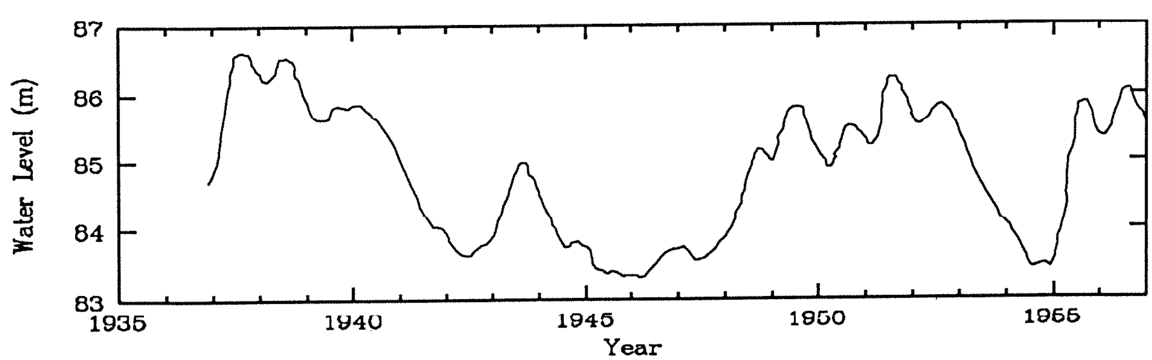


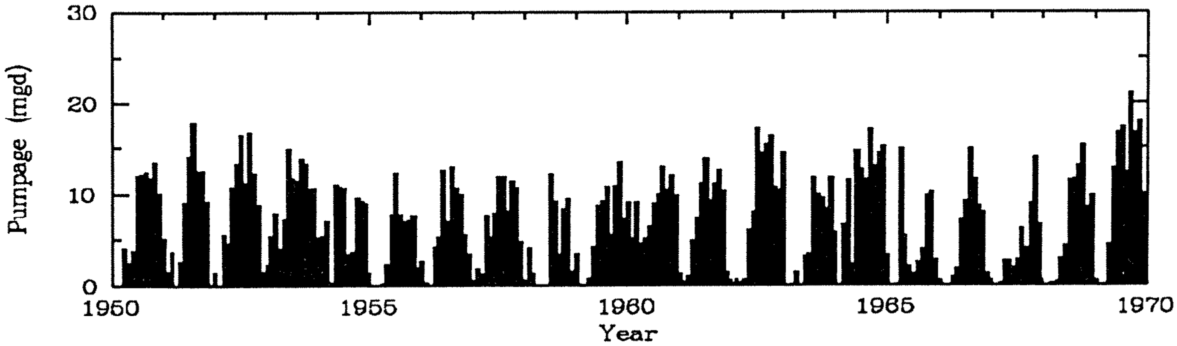
Figure 57. Monthly water level in Schofield Shaft, O'ahu Island, 1937–1956

wells in the Pearl Harbor area (data from USGS, Honolulu) show no correspondence with the severe droughts of 1953 and 1973. It is intuitively expected and analytically expressed in an equation derived by Schmorak and Mercado (1969), that well depth and pumping rate are key parameters affecting the chloride concentration of pumped water. The amount of upconing, z, beneath a well of a certain depth for a given pumping rate can be estimated from the equation,

$$z = \frac{\rho_f Q}{2\pi KL(\rho_s - \rho_f)}$$

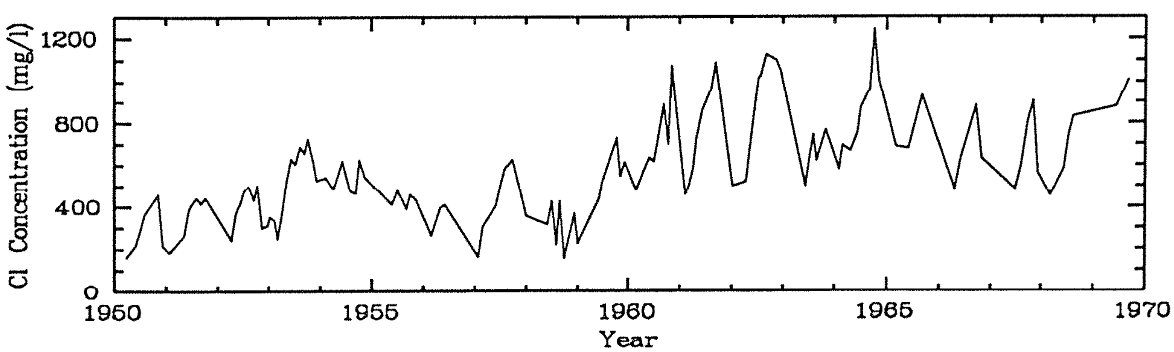
where z is rise in the saltwater-freshwater interface, ρ_f the density of freshwater, Q the well discharge, K the horizontal hydraulic conductivity of the aquifer, L the depth to saltwater interface from bottom of well before pumping, and ρ_s the density of saltwater. Larger z's will result from larger Q's and from smaller L's. Deeper wells yield smaller L's. The relation between pumpage and chloride is clearly seen in the records from a deep and a shallow well that tap the Pearl Harbor aquifer. The deep Waipahu Pump 6 Well (Figs. 58–59) penetrates 213 m (700 ft) below sea level to near the transition zone between fresh and salt water. The annual cycle of pumpage, ranging from 0–0.9 m^3/s (0–600 mil gal/mo), causes the chloride concentration to fluctuate several hundred milligrams per liter over the year. Waiawa shaft (Figs. 60–61) penetrates to only 6 m (20 ft) below sea level, and the annual cycle of pumpage, 0.6 to 0.9 m^3/s (400–600 mil gal/mo) barely affects the chloride concentration. The dramatic decline in pumpage, from 1977 to 1979, had the unexpected effect of increasing the chloride concentration of water pumped from Waiawa Shaft. This result has been attributed to the fact that the shaft draws water from near the top of the freshwater lens where irrigation return flow from fields irrigated by Waipahu Pump 6 has accumulated. Under low pumping rates a large fraction of the pumped water comes from this degraded zone (Tenorio, Young, and Whitehead 1969; Mink and Kumagai 1971; Hufen, Eyre, and McConachie 1980; Eyre 1983, 1987).

KONA AQUIFER NEAR KEAUHOU. To determine the relative importance of drought conditions versus pumping rate on the chloride concentration of water pumped from the Kona aquifer near Keauhou, the rainfall, drought index, chloride concentration, and pumping rate are analyzed (Figs. 62–64). In this part of North Kona the freshwater lens is about one-third the thickness of the lens in the Pearl Harbor aquifer and the residence time of groundwater is 20% shorter. At the four wells in the Kahalu‘u well field, which penetrate from 9–15 m (30–50 ft) below sea level, and which pump from 0.04–0.07 m^3/s (1–1.5 mgd), chloride concentration ranges from 40 to 80 mg/l. More dramatic, and more important to the water supply of North Kona, is the performance of Kahalu‘u shaft (Fig. 64). The shaft was excavated to just below sea level (1.5–3 m [5–10 ft] below the water table) and presently yields 0.3 m^3/s (6 mgd). Contributing to



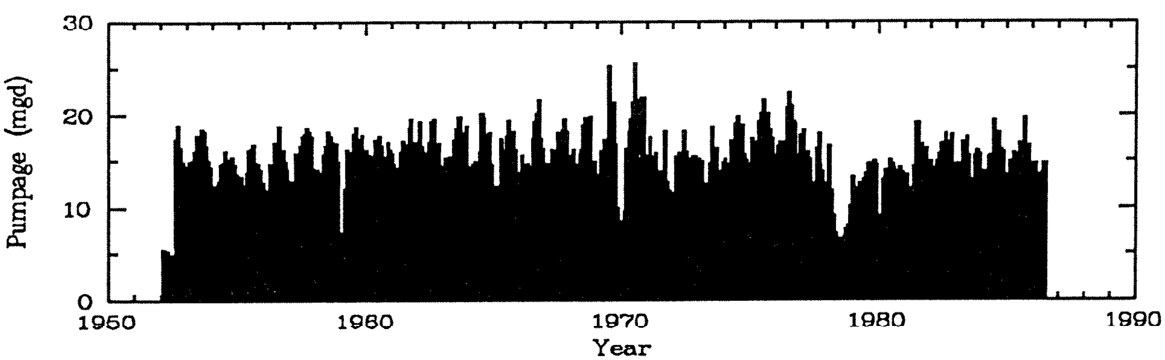
SOURCE: Eyre (1987).

Figure 58. Monthly pumpage for Waipahu Pump 6 Well, O'ahu Island, 1950–1969



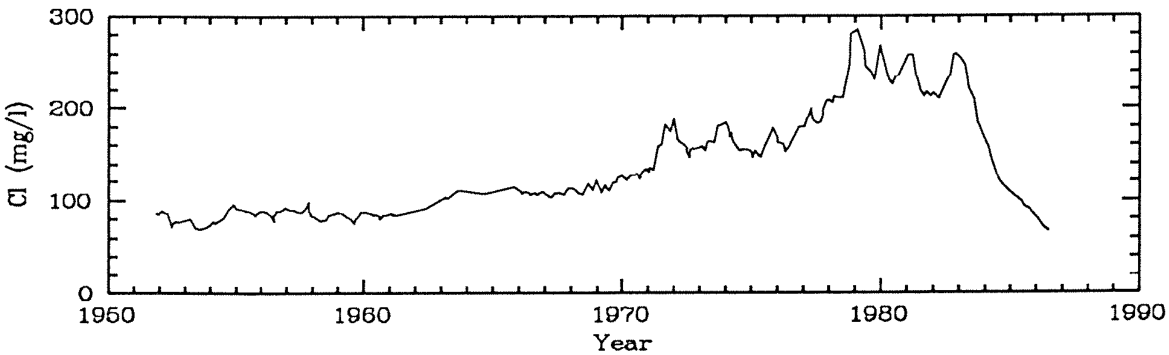
SOURCE: Eyre (1987).

Figure 59. Monthly chloride concentration for Waipahu Pump 6 Well, O'ahu Island, 1950–1969



SOURCE: Eyre (1987).

Figure 60. Monthly pumpage for Wai'awa Shaft, O'ahu Island, 1952–1986



SOURCE: Eyre (1987).

Figure 61. Monthly chloride concentration for Wai'awa Shaft, O'ahu Island, 1952–1986

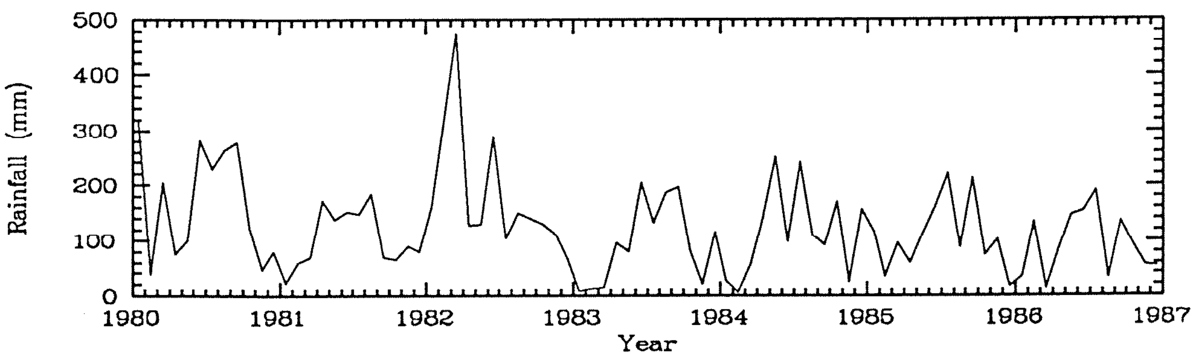


Figure 62. Monthly rainfall at Kainaliu, Hawai'i Island (Sta. 73.2), 1980–1987

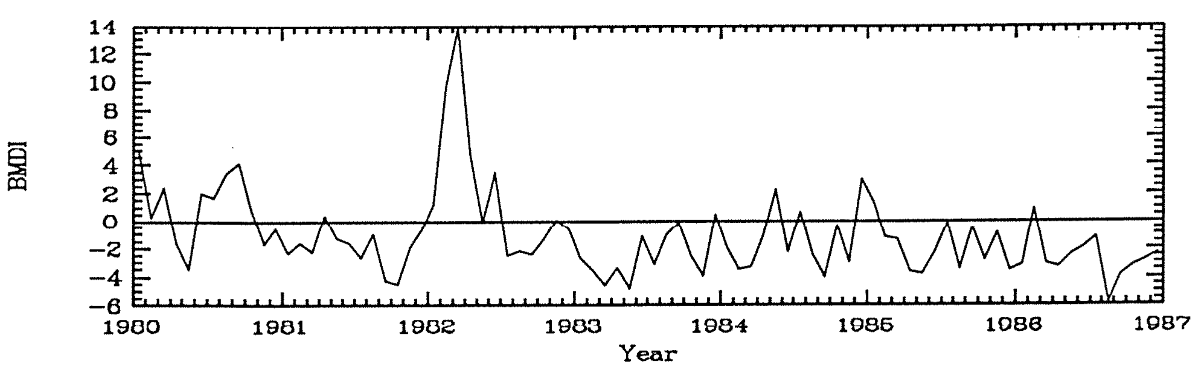


Figure 63. Monthly BMDI at Kainaliu, Hawai'i Island (Sta. 73.2), 1980–1987

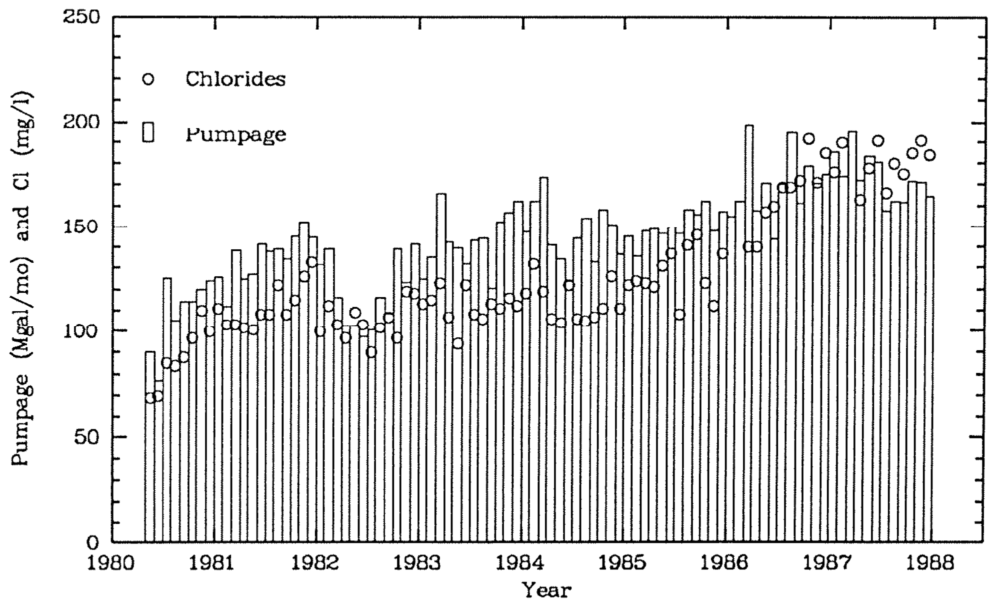


Figure 64. Monthly pumpage and chloride concentrations for Kahalu'u Shaft, Hawai'i Island, 1980–1987

the high chloride concentration at Kahalu'u shaft may be the fact that, beneath the pumps, holes were dug to approximately 6 m (20 ft) below sea level to allow the pump bowls to be set deeper than the tunnel invert. Pumping began in 1979 at a rate of 0.1 m^3/s (3 mgd) with a chloride concentration of 70 mg/l. Pumpage through 1987 generally increased and chloride concentrations rose and fell with fluctuations in pumping rate, rising to nearly 200 mg/l. The correspondence between chloride concentration and pumpage is apparent in the time series of chloride and pumpage shown in Figure 64 and in the scatter plot of chloride concentration versus pumping rate shown in Figure 66. In question is the role of pumpage from the other Kahalu'u wells and rainfall fluctuations on the chloride concentration at the shaft. Pumpage from the Kahalu'u wells has been relatively constant (Fig. 65) and cannot explain the rising chlorides at the shaft. On the other hand, deficits in rainfall, relative to mean rainfall do show a correspondence with times of rising chloride concentration. Shown in Figure 63, the drought index declined (the climate was becoming drier) from mid-1980 to late-1981, and chloride concentrations rose during that period (Fig. 64). The early part of 1982 was wet and chloride concentrations declined. The period 1983 to 1986 was moderately dry to normal and chloride concentrations were stable with a slight increase. The period from 1986 through the first half of 1987 was very dry and chloride concentrations increased markedly. Rainfall was normal in the latter half of 1987 and chloride concentrations were stabilized. From these data it appears that

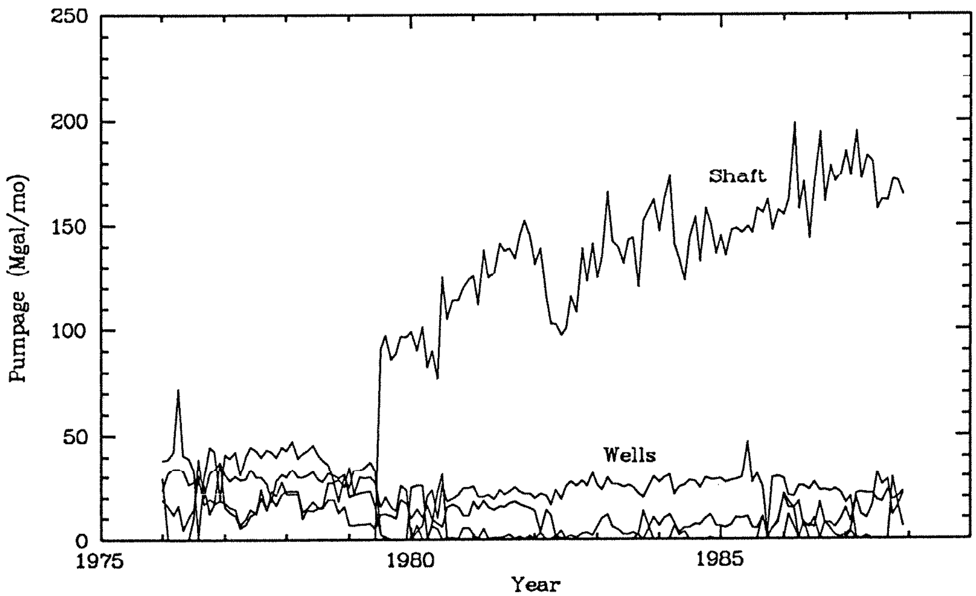


Figure 65. Monthly pumpage for Kahalu'u wells and shaft, Hawai'i Island, 1976–1987

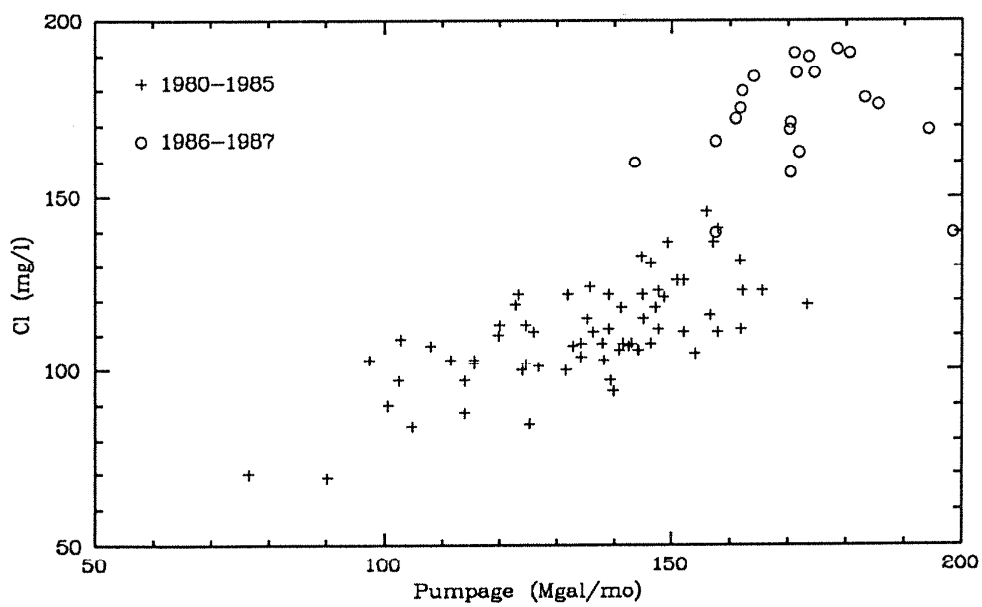


Figure 66. Scattergram of chlorides vs. pumpage at Kahalu'u Shaft, Hawai'i Island

rainfall, as well as pumpage, affect the chloride concentration of water pumped from the relatively thin Kona aquifer.

DROUGHT AND GROUNDWATER. This analysis has shown that in the thick Pearl Harbor aquifer reduced recharge during droughts may cause a decrease in freshwater lens thickness, but such decreases are too small to have an effect on the chloride concentration of pumped water. The evaluation shows that increased pumpage is the predominant cause of increased chloride concentration and that chloride concentrations can be manipulated by management of pumpage. Variations in rainfall must be considered primarily due to the demand for water during dry periods. In the thin Kona aquifer, on the other hand, the transition zone between fresh and salt water is much nearer the pump intakes and small changes in lens thickness associated with reduced recharge during droughts may bring salt water within the radius of influence of the pump. As in a thick aquifer, pumping rate and well depth are probably the predominant factors affecting the quality of pumped water.

DROUGHT MANAGEMENT

Water Consumption, Price, and Rainfall in Honolulu

In periods of drought, managers of urban water systems face a number of unusual pressures. First, the lack of rainfall usually means that demand for purchased water rises. The extent of this increase varies from place to place, particularly on O‘ahu with the high variability between the island's microclimates. Second, in some locales, supply, in the sense of source capacity, decreases if reservoirs are drawn down or wellheads decline. These pressures lead predictably to a situation of excess demand: consumers want more than the water system can supply at the going price. In the face of this excess demand, all the usual pressures from customers (and perhaps their political representatives) to keep water rates as low as possible remain in full force. A common response is a program similar to that of Los Angeles Mayor Tom Bradley in the face of his city's anticipated water crisis: a set of restrictions requiring customers to limit their water use.

That these programs fail to satisfy everyone concerned is a given, and a well-documented one at that. Whether an alternative approach would leave everyone better off is equally widely discussed.* Of particular interest to economists has been the proposition that the drought could be handled like any other situation of excess demand, by simply increasing the price of water and allowing buyers to adjust accordingly their consumption. In more technical terms, the question is whether the price elasticity of demand for water is high enough to choke off excess

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*See *Wall Street Journal*, Wednesday, 23 May 1990, p. A20.

demand, given any politically acceptable price increase and given physical conditions of the drought.

The general question of price elasticity of water demand has been much studied. Howe and Lineweaver (1967) and Howe (1982) used highly aggregated national data to show that residential demand for water is not completely inelastic. Others have used household survey data (Danielson 1979; Moncur 1984) and have addressed the specific question of price elasticity in periods of drought (Moncur 1987, 1989). Estimation techniques have ranged from ordinary least squares to sophisticated time series procedures (Shaw and Maidment 1987) and have incorporated a variety of special features of pricing structures (Billings and Agthe 1980). This report retains the central thrust of economic analysis common to preceding work, but uses data aggregated only to the level of administrative districts within a given urban water system, namely, Honolulu, Hawai'i.

WATER DEMAND MODEL. Standard economic theory suggests that the quantity of water a consumer will want to purchase from vendors like the Board of Water Supply (BWS) depends on three types of parameters: (1) the price of water, P_W; (2) prices of substitutes or complements for such water, P_S; and (3) income, Y. Substitutes for BWS water include water-efficient appliances, xeriscape gardening, and especially rainfall. Rainfall, however, is a somewhat unusual substitute commodity in that it comes in unknown amounts and at unknown times, more or less completely outside the control of the consumer; it is a parameter rather than a choice variable. Also, unlike other substitute commodities, rainfall has no price.

A simple model will yield the results expected on intuitive grounds: demand for purchased water is a declining function of its own price as well as of rainfall. It is plausible that, given general levels of water rates currently in force, other substitutes for purchased water, such as xeriscape gardening and low-flow toilets will affect the demand for water only very little if at all. We ignore these factors for the present. Clearly, many consumers will want to purchase more water from the BWS during relatively dry periods than when it rains in greater abundance, other things held the same. In accordance with standard procedure, assume a utility-maximizing consumer faced with the choice between spending money income, Y, on two goods: purchased water, W, and other goods and services (perhaps including savings), S. The total amount of water consumed thus becomes $W + \gamma R$, where R is a measure of rainfall and γ indicates the degree to which rainfall substitutes for purchased water. (For example, if nature delivers a given amount of rain in torrents, much of it becomes runoff rather than seeping into the ground. An equivalent amount of purchased water, by contrast, could be applied more slowly, providing optimal moisture, in terms of plant growth, for a longer period of time.) Hence one may express the consumer's utility function as $U[(W + \gamma R),S]$. For this project, let us assume that this function relates to some given period, say a month or a week, and accordingly ignores seasonality as well as purely random influences.

As with other commodities, a rational consumer chooses a level of water consumption via a standard process of utility maximization, subject to an income constraint:

$$\text{maximize } U[(W + \gamma R),S] \qquad \text{subject to } Y = P_W W + P_S S \tag{M-1}$$

where P_W and P_S denote prices of BWS water and of other goods and services. (Both price variables are in real terms, i.e., deflated by the consumer price index or some other appropriate measure of the value of the currency unit.) Rainfall, of course, is a parameter and not a variable of choice in this problem; consumers are assumed to choose W in the full knowledge of R. With utility stated in this general form, one can only say that, assuming continuity and differentiability, a standard Lagrangian maximization process will generate conditions describing the optimal combination and levels of W and S. In principle, from these conditions we can derive a function relating demand for BWS water W to parameters of the problem, P_W, P_S, Y and R. If the utility function takes the form $U = A(W + \gamma R)^{\alpha} S^{\beta}$, (A, α, and β are positive constants) then the Lagrangian is

$$L = A(W + \gamma R)^{\alpha} S^{\beta} + \lambda(Y - P_W W - P_S S) \tag{M-2}$$

and first-order conditions are:

$$A\alpha(W + \gamma R)^{\alpha-1} S^{\beta} - \lambda P_W = 0 \tag{M-3}$$

$$A\beta(W + \gamma R)^{\alpha} S^{\beta-1} - \lambda P_S = 0 \tag{M-4}$$

$$Y - P_W W - P_S S = 0\,. \tag{M-5}$$

Solving for the demand function $W = f(P_W, P_S, Y, R)$ yields:

$$W = \left[\frac{\alpha Y}{P_W(\alpha + \beta)}\right] - \left[\frac{\beta \gamma R}{(\alpha + \beta)}\right]. \tag{M-6}$$

This demand function is downward sloping with respect to both the price of purchased water and the amount of rainfall:

$$\frac{\partial W}{\partial P_W}, \frac{\partial W}{\partial R} < 0\,. \tag{M-7}$$

Hence a simple—perhaps overly simple—model leads one to hypothesize that empirical measurement of a water demand function will yield negative coefficients for both the price and the rainfall parameters. Of course, these results depend on the particular function specified here for utility. While one would not want to claim too much on the basis of this formulation, a variety of other functional forms would yield substantively similar results.

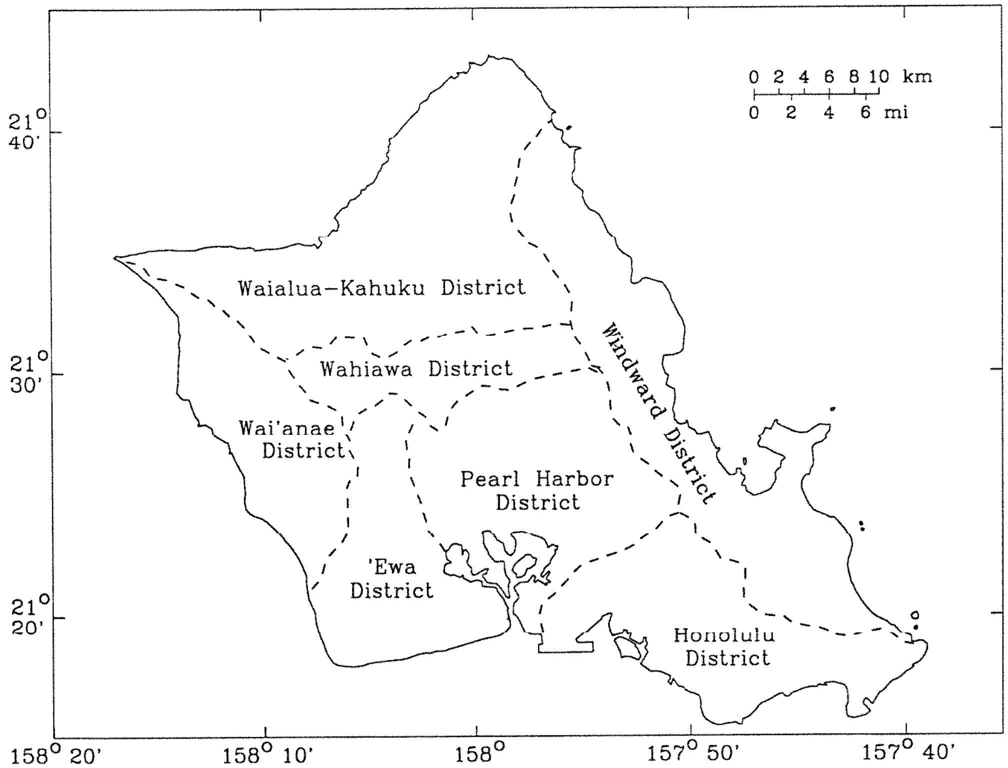
Other variables may enter as well. First, to some degree the recent history of rainfall may substitute for water purchased in the current period. Whatever the level of rainfall this month, if last month was extremely wet, then a typical household will use less for lawn watering than if the month had been extremely dry. Hence, in the following empirical work rainfall enters in various lag specifications.

Second, institutional factors can be expected to impact the consumer's decision about how much water to purchase. The BWS, for example, may permit lawn watering activity only in cool hours of the day, building codes often limit the choices for water-using appliances, the law may forbid the use of some methods of irrigation or certain uses of water.

For estimation purposes it is important to note that the behavior of the rainfall variable described earlier, as well as other climatic and economic variables, leads to error terms that are correlated over time. Seasonality, ignored in the interest of simplicity, will affect demand as well as supply. In addition, a homeowner with substantial investment in water-using appliances, lawns, and gardens probably will not wish to abandon that investment at the first sign of increased water prices. Hence, we posit below models with autoregressive moving average error structures.

DATA. The BWS organizes O'ahu into seven districts for administrative and data collection purposes (Fig. 67). In general, good quality data is available for each district, although the 'Ewa and Wai'anae districts are combined here for lack of comparable data in a few of the early years of the period studied. The models use monthly data for the period July 1961–June 1986 on four variables: (1) pumping (mgd) from BWS annual reports (1961–1986), (2) rainfall (in./100), (3) nominal water rates, taken as the quantity charge (for the last block, if applicable; in dollars per thousand gallons, BWS annual reports), and (4) the Honolulu Consumer Price Index (all urban consumers: Bank of Hawaii 1989). Also, a dummy variable represents months when water-use restriction programs were placed in effect by the BWS.

One rain gage station was chosen in each district to represent rainfall for that entire district. Available rain gage records required minor "patching" via interpolation routines to fill in missing observations, but such instances were scattered over time and few in number. Also, the Honolulu CPI is not available on a monthly basis. Quarterly data were interpolated for missing months. Unfortunately, no data on income are available in BWS districts, much less on a monthly basis, and thus leave the demand functions incompletely specified. Some insight into the effect of income on water demand is covered in Moncur (1987), which uses a household-level survey data set.



SOURCE: Board of Water Supply (1982).

Figure 67. O'ahu water use districts

As constructed, the data sets provide a complete record for each BWS district over the period July 1961–June 1986, although lag specifications require dropping as many as 26 observations from the beginning of this period. Also, to avoid breaks in the trend or variance of the data for two districts ('Ewa-Wai'anae and Windward) the analysis for those districts omits data prior to July 1972.

The data for the Wahiawa district pose several special problems. The development of Mililani Town in the late 1960s fundamentally changed the pattern and trend of pumpage for the Wahiawa district. Also, the data show clearly an abrupt change in 1983 when traces of pesticide were discovered in major wells. Pumping was shut down for a period during which time carbon filtration processes were installed and had not recovered by June 1986, when our data set ends. Hence the omission of Wahiawa.

ARIMA MODELS. When estimating the relationship between two variables, such as water use and rainfall, one might specify an equation of the sort,

$$q_t = \alpha + (\beta R_t + e_t) \tag{M-8}$$

where e_t is the error term, and apply ordinary least squares regression to estimate the parameters α and β. However, one assumption of the ordinary least squares model is that successive values of the error term are independent, $E(e_t\, e_s) = 0$ for t not equal to s. Time-series data such as is provided by historical monthly pumpage and rainfall figures as often as not violate this assumption. If, for example, pumpage in July is exceptionally high (or low) then pumpage in August and September is likely to be high.

This interconnectedness or nonrandomness between successive values of a time series variable can take one of two forms. A variable q_t which is well explained as a function of its own past values is said to be *autoregressive* in nature. In general, such a variable can be written

$$q_t = a + b_t q_{t-1} + b_2 q_{t-2} + \ldots + b_k q_{t-k} + e_t \,. \tag{M-9}$$

Similarly, one might specify pumpage as a combination of past error terms e_t, in which case the model is said to be a moving average model,

$$q_t = a + b_1 e_{t-1} + b_2 e_{t-2} + \ldots + b_k e_{t-k} + e_t \,. \tag{M-10}$$

Bring both autoregressive and moving average elements into the equation and making various transformations to the data defines an Autoregressive Integrated Moving Average (ARIMA) model. Incorporating other variables—price, income and rainfall, in the present study—into the analysis results in a *transfer function* model, such as those estimated below and listed in Appendix B.

Just how many past values of q_t or e_t (or both) to include in an ARIMA equation is not obvious but is the object of a series of techniques pioneered by Box and Jenkins (1976). Their procedures begin by transforming the series, if necessary, to remove any nonstationarity (roughly speaking, long-term trend in either the mean or variance or both), then examining the autocorrelation and partial autocorrelation functions from the resulting transformed series. The autocorrelation function measures the correlation between contemporaneous and lagged values of the time series using the formula,

$$r_k = \frac{\sum_{t=1}^{n-k} (Y_t - \bar{y}(Y_{t+k} - \bar{y}))}{\sum_{t=1}^{n} (Y_t - \bar{y})^2} \tag{M-11}$$

for some arbitrarily established value of k. Partial autocorrelation coefficients, though more complicated in computation, indicate the degree of dependence of a variable q_t on its past value q_{t-k} when the effects of the intervening time lags ($q_{t-1}, q_{t-2}, \ldots, q_{t-k-1}$ are in some sense "partialled out."

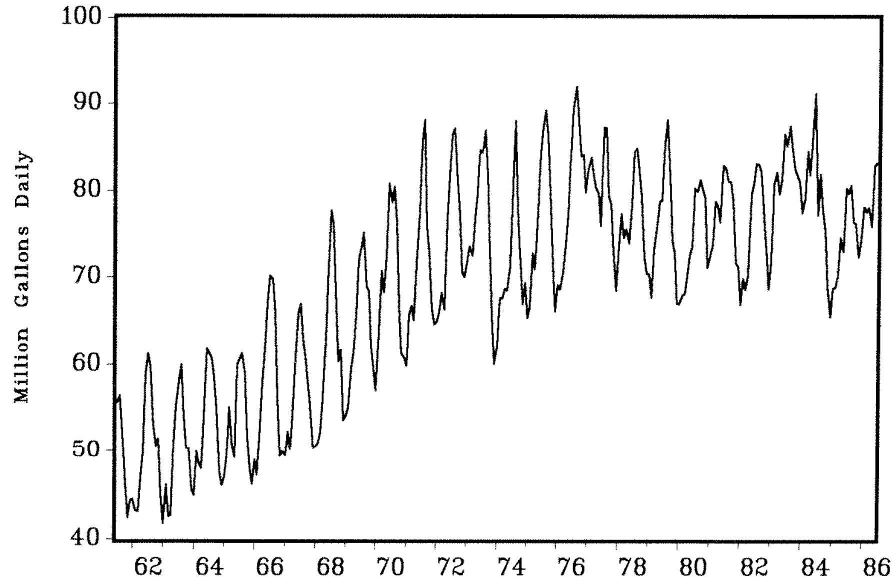


Figure 68. Monthly mean daily pumpage, Honolulu District, July 1961–June 1986

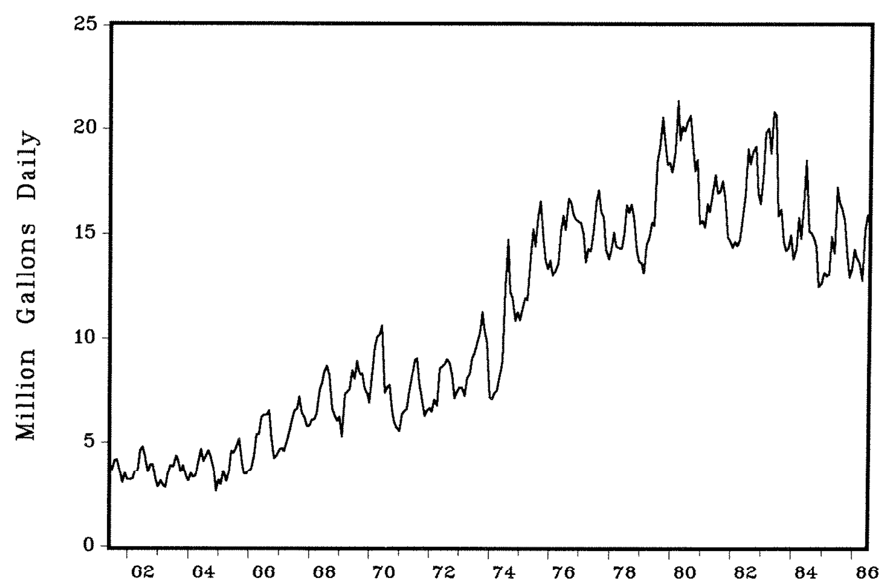


Figure 69. Monthly mean daily pumpage, Pearl Harbor District, July 1961–June 1986

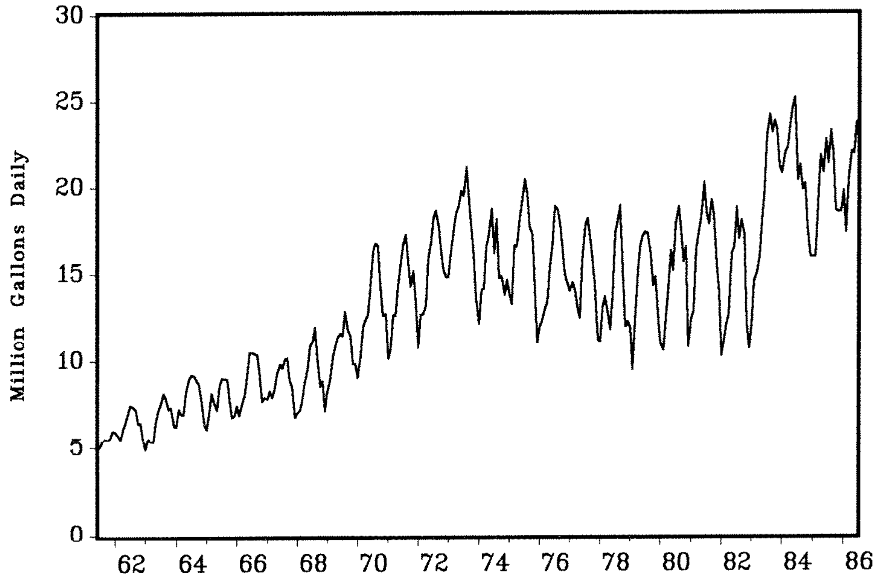


Figure 70. Monthly mean daily pumpage, ‘Ewa-Wai‘anae District, July 1961–June 1986

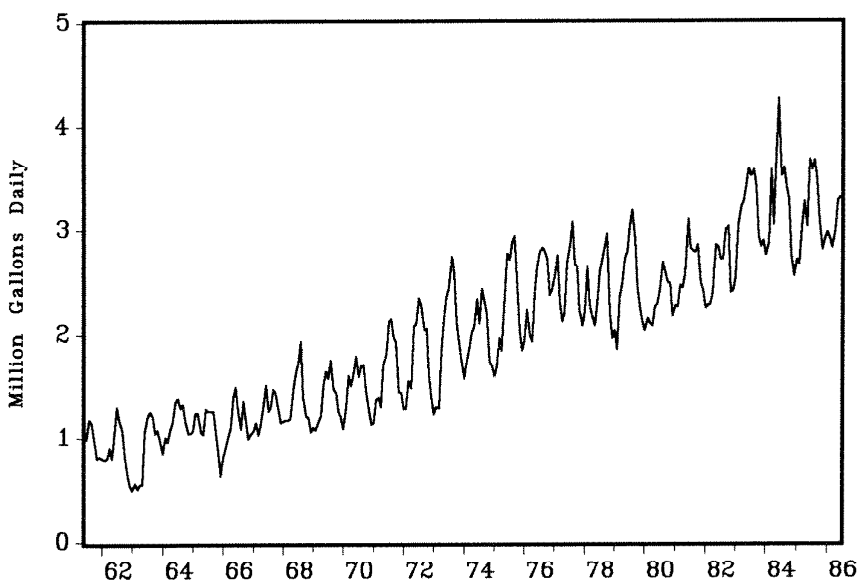


Figure 71. Monthly mean daily pumpage, Waialua-Kahuku District, July 1961–June 1986

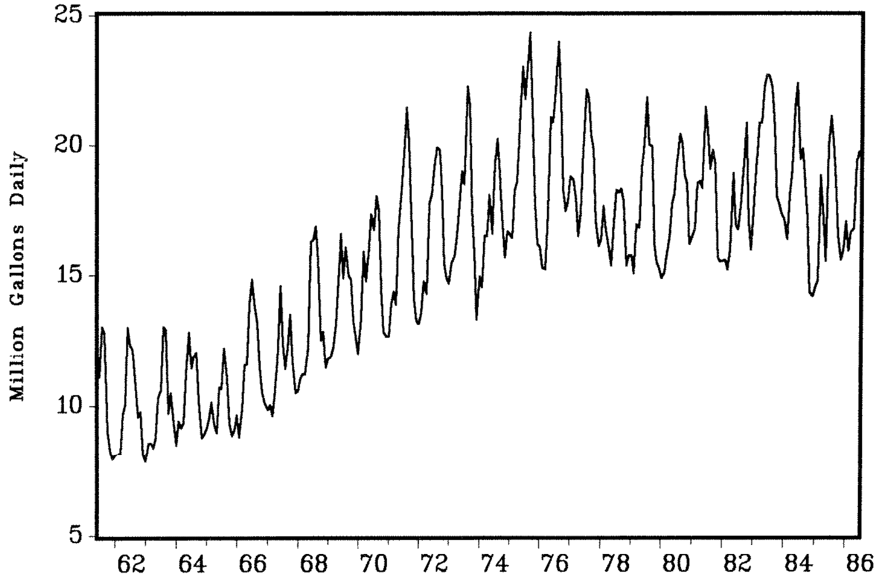


Figure 72. Monthly mean daily pumpage, Windward District, July 1961–June 1986

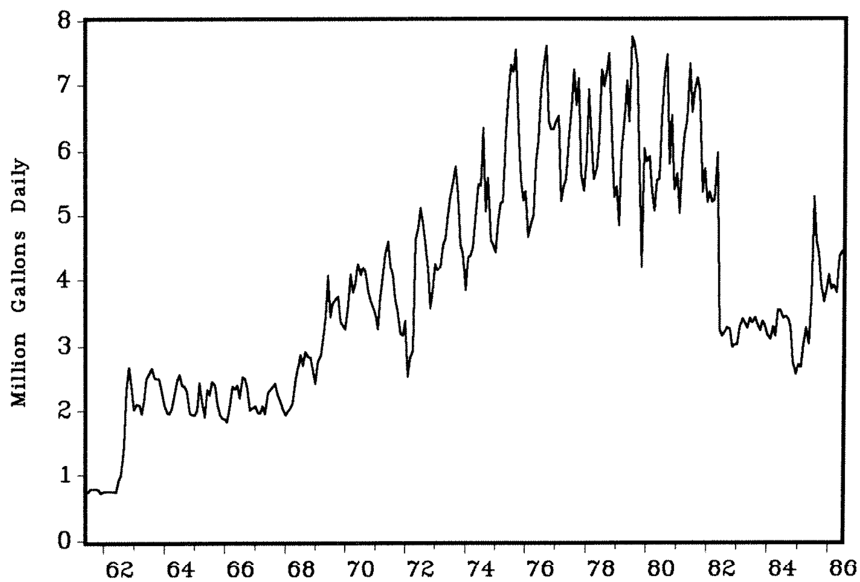


Figure 73. Monthly mean daily pumpage, Wahiawa District, July 1961–June 1986

ESTIMATION OF HONOLULU MODELS. Figures 68 through 73 show monthly mean daily pumpage for each of the six BWS districts. The same general process was used to estimate results in the five districts analyzed. I will describe in some detail the model for Waialua-Kahuku district, then present results for the other four.

Figure 71 shows monthly mean daily pumpage for the Waialua-Kahuku district. The data show a clear upward trend over the years and suggest nonstationarity in the variance as well. Hence the pumpage data were transformed first into logs and then second differences. The resulting series (Fig. 74) shows no discernable trend in either level or variance. The autocorrelations and partial autocorrelations shown in Figure 75 make clear the strong trends in pumpage data. A standard Box-Jenkins identification process leads to the noise model

$$(1-\phi B^{12})(1-\Phi B^{12})u_t = (1-\theta B)e_t \tag{M-12}$$

where B is the backshift operator, e.g., $B^{12}u_t = u_{t-12}$. Thus the model includes a 12-lag autoregressive term ϕ, a 12-lag seasonal autoregressive term Φ, and a single-period-lag moving average term θ. Cross correlations of the pumping variable (transformed) with (similarly transformed) rainfall and price variables suggest that rainfall and price, as well as rainfall lagged by one period, should also appear in the transfer function model, yielding

$$(1-B)^2 \ln q_t = \alpha + (\omega_1 + \omega_2 B)(1-B)^2 \ln R_t + \omega_3 (1-B)^2 \ln P_t + u_t \tag{M-13}$$

where q, R, and P denote respectively pumpage, rainfall and price. Equations (M-12) and (M-13) involve estimates of three coefficients ω_1, ω_2, and ω_3 associated with the substantive variables, plus three ARIMA coefficients ϕ, Φ, and θ plus the intercept α. These estimates appear in Tables 33.1–33.2. Error models and estimated equations are given in Appendix B.

To summarize, raw data on pumpage by BWS in the Waialua-Kahuku service district, q_t, was transformed (by taking $\log_e$ and then taking second differences) to eliminate nonstationarity. The same transformations were applied to data on price P_t, rainfall R_t and lagged rainfall R_{t-1}. The Box-Jenkins identification process was then applied, with the result suggesting use of a one-month-lagged autoregressive term MA(1) in Tables 33.1–33.2; a 12-month-lagged autoregressive term AR(12) and a 12-month-lagged seasonal autoregressive term SAR(12).

Other BWS districts have different patterns of consumption and rainfall as well as different trends and variation in growth of consumption, as indicated in the data in Figures 68 through 74. Accordingly, the Box-Jenkins process leads to unique error specifications and transfer function models for each district. In particular, other districts require less complex transformations of the original data. Appendix B lists the complete set of equations, corresponding to the numerical estimates in Tables 33.1–33.2.

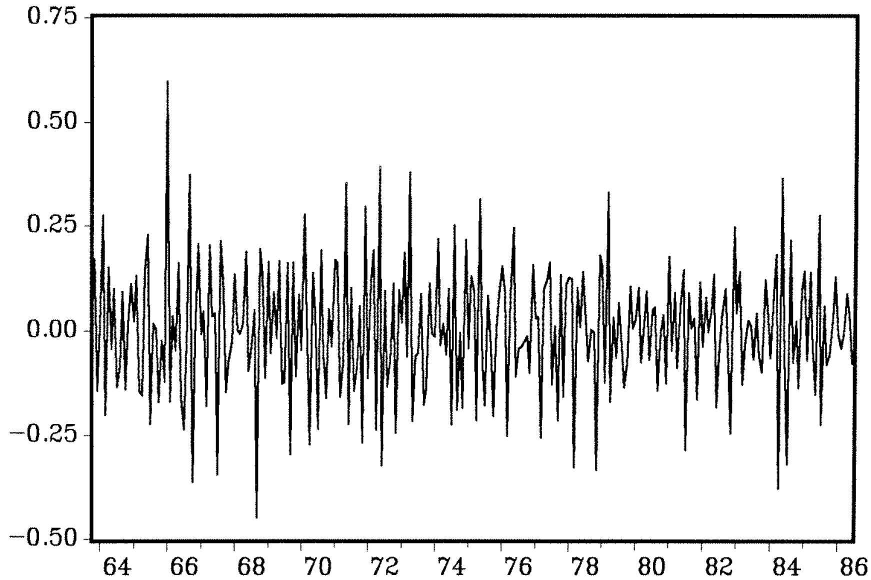


Figure 74. Transformed monthly mean daily pumpage (second difference of natural logarithm), Waialua-Kahuku District, Nov. 1963–June 1986

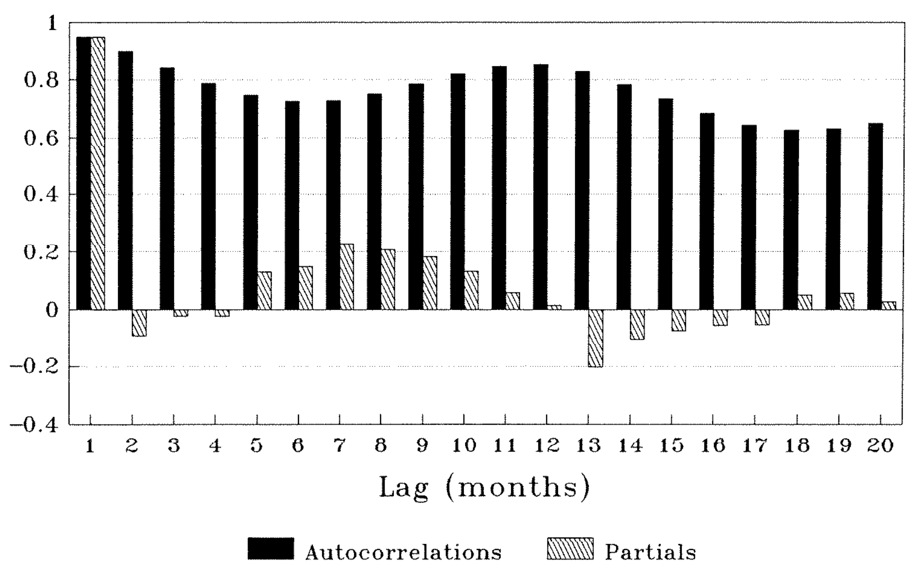


Figure 75. Autocorrelation and partial correlation coefficients, raw pumpage, Waialua-Kahuku District

RESULTS. *Micro TSP* (Hall and Lilien 1988) yielded the estimates appearing in Tables 33.1–33.2. Table 33.1 shows the estimated coefficients; while Table 33.2 shows error statistics and various other parameters of the estimation process. Notation is slightly different in the table, but the substantive variables Rain, $Rain_{-1}$ and Price are defined in the same manner as R_t, R_{t-1}, P_t. DUM is a dummy variable set equal to one for months in which drought restrictions were in place and zero if otherwise. The ARIMA parameters are here labelled MA(i), AR(i) and SAR(i), corresponding to θ, ϕ, and Φ in the equations in Appendix B. The MA(1) coefficient, for example, corresponds to the parameter θ in the term $(1\text{-}\theta B)e_t$ of equation (M-12).

Printed beneath each estimated coefficient is a t-statistic enclosed in parentheses. In general, a t-value of greater than two supports rejection of the null hypothesis that the associated coefficient is zero. Here, the variables q, P, and R have been transformed as indicated in Table 33.2, next-to-last column.

Error statistics reported here include the standard error of estimate, the adjusted coefficient of determination R^2, and the Durbin-Watson statistic DW. Values of DW close to 2.00 indicate a lack of serial correlation remaining in the identified model. The table also gives the estimation period (63.09 means September 1963, and so on), the mean value of the rainfall series used for this estimation, a definition of the dependent variable in the estimated equation and the mean value of this variable. For Honolulu district, for example, $(1\text{-}B)^2q_t$ indicates that the raw pumpage data was transformed into second differences,

$$(1-B)^2q_t = (1-2B+B^2)q_t = q_t - 2q_{t-1} + q_{t-2} = (q_t\text{-}q_{t-1}) - (q_{t-1} - q_{t-2})\,.$$

Substantively, as expected from the demand model of equation (M-7), Rain coefficients for all five water districts are negative and, judging by t-statistics, all differ significantly from zero. (With the large samples dealt with here, the coefficient estimates follow an approximately normal distribution. Hence any coefficient with a t-statistic over 1.96 would be less than 5% likely to occur by chance if, in fact, the coefficient is zero. Since all t-statistics in the Waialua-Kahuku model (excepting only the intercept) exceed two, one can reject the null hypothesis that, in fact, the coefficients are zero.) Rainfall enters this equation contemporaneously (R_t) as well as with a one period lag (R_{t-1}).

The lagged rainfall variable for Waialua-Kahuku also has a negative and significant coefficient.

Price variables show mixed results. The Honolulu, Pearl Harbor, Waialua-Kahuku, and Windward districts give negative values, in accord with economic theory, though the first two are indiscernible from zero. For the latter two districts, the negative price coefficients are not only significant but quite robust to variations in specification. Honolulu and Pearl Harbor are

TABLE 33.1. TIME SERIES ESTIMATES OF BOARD OF WATER SUPPLY PUMPAGE

District*	Const	RAIN	$RAIN_{-1}$	PRICE	DUM	MA(1)	MA(11)	MA(12)	AR(1)	AR(11)	AR(12)	SAR(12)
Honolulu	0.025	-0.003		-0.127	-0.185	-0.933					-0.423	0.645
		(-9.00)		(-0.30)	(-0.27)	(-15.01)					(-8.43)	(13.99)
Pearl Harbor	0.003	-0.001		-0.004	-0.048	-0.813			-0.909		-0.120	0.289
		(-4.78)		(-0.03)	(-0.41)	(-9.67)			(-14.97)		(-2.14)	(4.89)
Ewa-Waianae	16.297	-0.001		14.919	0.011	0.174			0.736	0.220		
		(-3.38)		(1.79)	(0.02)	(1.89)			(15.21)	(5.10)		
Waialua-Kahuku	0.000	-0.58	-0.023	-0.106		-0.939					-0.352	0.557
		(-11.36)	(-4.59)	(-6.56)		(-15.03)					(-6.90)	(11.82)
Windward	20.540	-0.001		-10.377		0.130	-0.423	-0.245	0.552	0.507		
		(-4.88)		(-2.13)		(1.29)	(-4.04)	(-2.66)	(9.14)	(8.03)		

*Wahiawa District omitted due to poor data. t-statistics in parentheses. RAIN and $RAIN_{-1}$ denote contemporaneous and lagged rainfall variables: PRICE is the marginal price, deflated; all transformed in the manner indicated under "dependent variable" below; DUM is a dummy variable indicating the presence of water-use restrictions; MA(i) indicates moving average coefficient with lag of i months; AR and SAR are autoregressive and seasonal autoregressive terms.

TABLE 33.2. TIME SERIES MODEL ERROR STATISTICS

District	S.E.R.	Adjusted R^2	DW	Estimation Period	Mean Rainfall*	Dependent Variable†	Mean of Depend. Var.
Honolulu	3.485	0.58	2.05	63.09–86.06	331.5	$(1-B)^2 q_t$	-0.00504
Pearl Harbor	1.026	0.51	2.17	63.09–86.06	249.3	$(1-B)^2 q_t$	0.00073
Ewa-Waianae	1.573	0.79	1.43	72.07–86.06	189.5	q_t	16.71
Waialua-Kahuku	0.094	0.64	2.26	63.11–86.06	412.6	$(1-B)^2(\ln q_t)$	0.00056
Windward	1.228	0.72	2.00	72.07–86.06	636.3	q_t	18.07

*Mean monthly rainfall, July 1961–June 1986.
†q_t denotes raw pumpage in month t; B is the backward shift operator, $B^n q_t = q_{t-n}$.

the most densely populated of all BWS districts and probably contain the highest density of large apartments and condominiums. If so, the lack of metering for individual dwelling units explains the failure of price to account for any significant proportion of the variation in district pumpage. Waialua-Kahuku and Windward districts, in contrast, are suburban and semirural, with predominantly single-family, individually metered dwellings.

The anomaly seems to be the price coefficient for the ‘Ewa-Wai‘anae district, which is large and positive, though arguably insignificant. This district has the lowest amount of rainfall on the island. It would not be surprising to find that price elasticity of demand is very near zero.

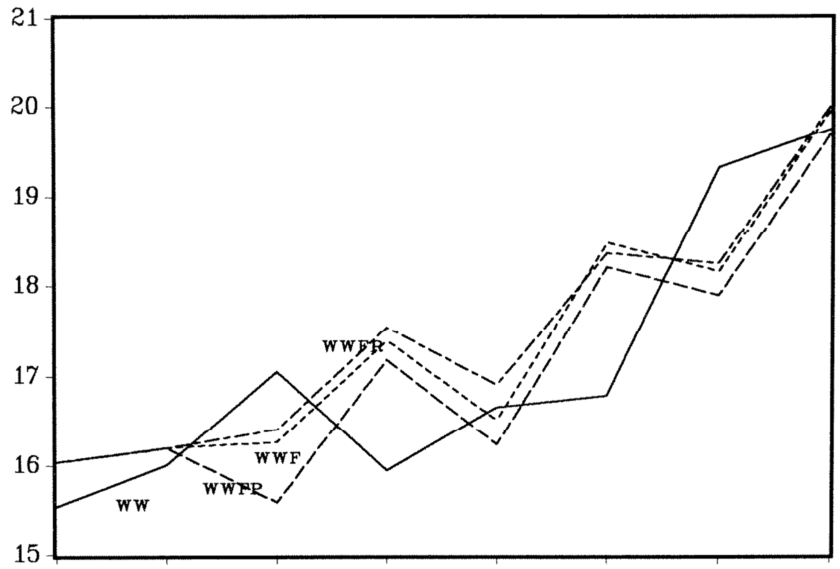
The dummy variable included in the first three equations was an attempt to pick up effects of the BWS water-use restriction programs during episodes of drought in the fall of 1976 and in the fall of 1984. None of these variables contributes much to an explanation of pumpage and were omitted from the Box-Jenkins process for the last two districts. Apparently, daily pumpage data is needed to bring out the impact of these restrictions.

USE OF THE MODELS. Applying the equations in Tables 33.1–33.2 is best done with the TSP program; the complex error terms and data transformation make computation by hand very difficult. Figure 76, however, shows the kind of result possible with these equations. For illustrative purposes, the Windward district equation has been used since the quantity, rainfall, and price variables need no transformation. The curve WW is raw pumpage in the Windward district. WWF is the value forecast (calculated and charted only for January to June 1986) by the Windward equation in Tables 33.1–33.2, using observed values of price and rainfall. WWFP is a simulation of what would happen if price were increased by 25%. This line lies significantly below the WWF line, indicating decreased pumpage because of the conservation induced by the higher price. The 25% increase in price leads to decreases in pumpage of between 1.3 and 4.3% in the six months simulated here.

By contrast, the WWFR line shows simulated values of pumpage on the assumption that rainfall was 50% lower than actually observed. The juxtaposition of the two lines suggests that increases in pumpage due to drought could be compensated for by a reasonable increase in price.

Using these equations to forecast pumpage is fraught with uncertainty, as is any forecast. Nevertheless, the estimated coefficients as well as the simulations of Figure 76 confirm the relationships we expected on the basis of theory, and, at the very least, point to the usefulness of a time-series approach to studying these relationships.

SUMMARY. The equations in Tables 33.1–33.2 show that, as hypothesized, Honolulu consumers will respond to a higher price by decreasing the amount of water they consume. The equations also yield estimates of the magnitude of the relationship between rainfall and consumption. Based on monthly service-district pumpage data, these results are generally



NOTE: WW = actual pumpage, WWF = pumpage forecast based on equation in Table 33, WWFP = pumpage forecast with 25% price increase, and WWFR = pumpage forecast with 50% lower rainfall.

Figure 76. Windward District pumpage, actual and forecasts

consistent with previous work based on islandwide data, though in some districts the price coefficient is stronger than the comparable islandwide estimate (see Moncur 1989).

With the ARIMA coefficients as well as the substantive variables, the results can produce approximations for *long-term* forecasting, although they are not appropriate for day-to-day managerial purposes. The time series techniques used here, however, could be adapted to that purpose, by using daily or even hourly data.

Still needed to enhance these results is some means of representing income in the equations. The lack of income misspecifics the theoretical relationship and may introduce bias into the estimates of Tables 33.1–33.2. Also, further statistical work at the Box-Jenkins identification stage should be directed toward an explanation of the anomalous positive price coefficient for the ‘Ewa-Wai‘anae district.

Allocating Water During Drought

At any given time, the available water resource is distributed among uses and regions in a well-defined pattern. When supplies are sufficient to meet all demands, conflict over water use is relatively subdued and decisions on water allocation are correspondingly simple. When available supplies are insufficient to meet demands, however, competition for water may grow and decisions on allocation can become complex.

This section treats the questions of how to determine allocation of water during drought and of the role that statistical information on *meteorological* drought can play in such a determination. First, the concept of allocation is discussed, four of its principal elements are identified, and the potential of different kinds of drought to effect changes in an existing allocation is highlighted. Next, key facets of the county water-management decision environment are identified, since they will at least partially determine the success of any procedure suggested for incorporating drought characteristics into water-allocation decisions. Following this comes the description of a model that utilizes information on patterns of past drought to help determine how existing water allocation should change in the face of a current or anticipated drought. An example of the procedure comprises the last section.

DROUGHT AND WATER ALLOCATION. Allocation of water will be used here to mean the deliberate distribution of water by use and region, where decisions on the distribution are taken by governmental authorities. Such allocation should consider, at a minimum, (1) the sources of supply and the amounts of water to be provided by each; (2) the demands (deficits or needs) of each use, where identical use classes may be distinguished by region; (3) the costs of supplying the demands; and (4) the benefits of supplying the demands. "Costs" and "benefits" are used in the broadest sense, meaning the full array of positive and negative consequences.

Drought has the potential to affect some or all of these four elements and hence the allocation itself. For example, during drought, demand commonly rises (irrigation requirements) and supplies fall (streamflow and reservoirs). Indeed, such effects are implicit in the definitions of the four principal types of drought, a distinction of more than passing importance to the task at hand. *Meteorological* drought refers to departures from "typical" or "normal" climatological conditions leading to drier than normal weather. Much of the difficulty in making this conceptual definition operational lies in the meaning of normal and typical and the precision given it. *Agricultural* drought refers to dryness as it affects crops and other plants of importance to agriculture and livestock. *Hydrological* drought refers to the insufficient availability of surface and ground waters to meet the demands placed upon them. Finally, *socioeconomic* drought occurs when social and economic disruptions result, directly or indirectly, when available water is unable to supply demands.

These distinctions are crucial in the recognition of drought as well as in the assessment of the supplies, demands, and consequences which correspond to any given allocation and which influence the determination of a preferred one. Both the general public and water managers commonly respond not so much to meteorological trends as to the effects that such trends have on society. Of particular relevance are agricultural conditions and such hydrologic indicators as stream flow and aquifer levels. Nevertheless, drought-related data available to water managers is commonly limited to studies of meteorological drought—statistical analysis of short- and long-term climatic patterns—with the result that such information may see little direct utilization in drought-management decisions. Yet, as illustrated in the following procedure, when linked to the other dimensions of drought climatic data can indeed play a useful role in drought decision making.

THE DECISION CONTEXT. Water allocation in the Islands is a public-sector task influenced by the desires and viewpoints of multiple decision makers and of a wide variety of groups, defined sectorally and spatially and affected by an allocation in different ways. As such, political criteria are undeniably important in the allocation decision, and an analysis based exclusively on a strict economic reckoning of benefits and costs would have only limited acceptance.

The county water-supply agencies plan, develop, manage, and operate the water-supply systems serving most of the residential and nonresidential urban uses in the islands. In contrast, most agricultural uses, some industrial uses (e.g., small hydropower plants for milling operations), and a small portion of residential uses (e.g., some resort communities) obtain water from private systems. In areas where groundwater pumpage is approaching sustainable yield, it has been proposed to grant county councils the power to allocate water among different land uses. The water-supply agencies would provide information on source limits and current use, and they might also play an advisory role in determining allocations. Although the proposal refers to scarcity brought on by continued growth in population and development, drought too can induce scarcity and a consequent need for new allocations. Thus, although the model described and illustrated in later sections has been designed for use by these agencies, the power of the agencies to determine ultimate allocations is limited.

An important aspect of the decision context concerns the agencies' perceptions of drought. In their normal operation, they respond not to meteorological trends but rather to the effects of such trends on society. As suggested in the previous paragraph, of particular relevance are such hydrologic indicators as stream flow and aquifer levels. Meteorological drought provides little direct stimulus for drought-related actions, whereas agricultural, hydrologic, and socioeconomic drought do. Since the geophysical analysis presented in this report focuses on the meteorological dimension, its direct utilization in water agencies' decision making presents a significant challenge.

AN ALLOCATION MODEL. At its most rudimentary, allocation requires the distribution of water from different types and locations of supply to various types and locations of demand (or need). Since drought is apt to affect both supplies and demands, the problem of allocation under drought is conceptually that of deciding the best way to alter predrought water distribution such that impacts on supplies and demands are taken into account. Figure 77 illustrates this concept by depicting a hypothetical allocation before a drought (Fig. 77a) and the

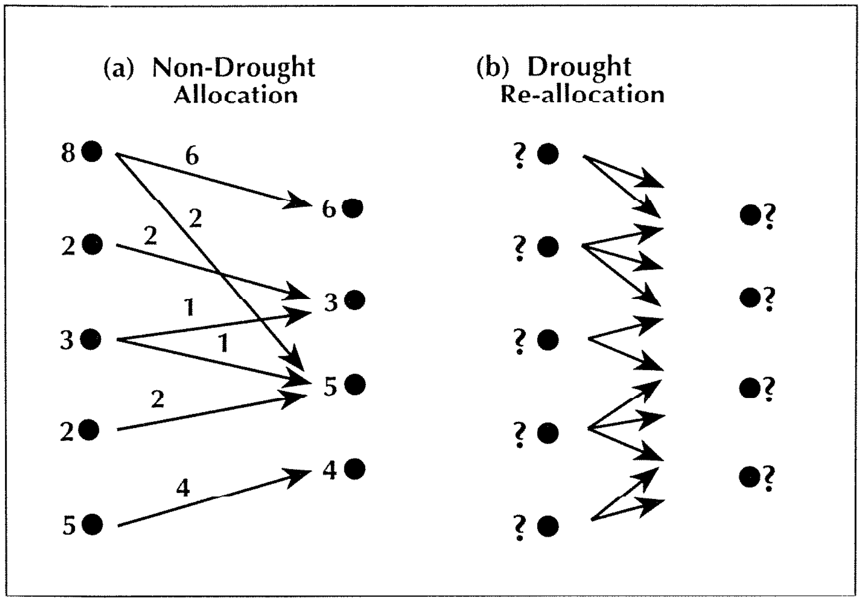


Figure 77. Water allocaton during drought: (a) How are supplies and demands in non-drought times altered by the drought, and (b) What should be the resulting redistribution?

effects of the drought on supplies and demands (Fig. 77b). In this example, available supplies are insufficient to meet demands. This is what we would expect, since in all but the meteorological type some form of deficit is the indicator of drought. Consistent with this is the observation that "available" usually refers to desirable rather than physical limits: just as withdrawing funds from capital reserves does not prevent a business whose expenditures exceed income from going in the red, so a town's pumping water from an aquifer beyond its sustainable yield does not eliminate the deficit. This distinction becomes important when it is deemed desirable (perhaps only in the short run) to overallocate available supplies.

Two major questions arise. First, how can we estimate the effect of drought on demands and supplies? Since lead time may be desirable, even required, to change an allocation, this question includes the problem of how to predict a drought. Also of interest here is the way in which statistical analysis of meteorological drought might aid in such predictions. Second, given the predicted effects upon available supplies and demands, how should a new allocation be determined? The following is a set of procedures to be used in answering these questions.

Estimating Drought Impacts. How a drought affects water supplies and demands depends on the location of the supplies and demands and on the severity of the drought. One way to estimate these overall effects would be to link direct and indirect effects through a cause-effect chain. One could then determine the relationship defining each link of this chain and, by appropriately combining them all, assess the ultimate consequences. Clearly, care is required so that the approach does not become overly reductionist and misrepresent, or miss altogether, important systemic characteristics of the set of individual relationships considered as a whole.

In the present context, three observations become vitally important. First, there may be no way, practicable or otherwise, to measure any of these drought-induced consequences in an objective manner. This means that people's judgments will be important and will need to be incorporated into the assessments. Related to this is the fact that effects will be felt upon more than one element of each relevant impact class (such as regions, societal sectors, water sources, and supply systems), and it will be useful to know how a given drought consequence affects one element as compared to another. Thus, relative impacts are important. Third, quantitative (based on ratio-scale data) rather than qualitative assessments will be more useful in determining water allocation since allotments as percentages of the total available supply are what is sought. The Analytic Hierarchy Process (AHP) offers an approach to estimating and evaluating such impacts that responds to these three desiderata (Saaty 1980). Because during the last decade the AHP has received considerable attention from decision scientists and practitioners alike, the remainder of this section discusses its application to water allocation during drought rather than the methodology *per se*. A concise elementary review of the AHP can be found in the Appendix C.

Drought Impacts as an Analytic Hierarchy. Hierarchical structures can be used to represent the effects upon water supplies and demands during and after a drought. Supply effects can be depicted for each source region through a four-level hierarchy. The apex of the hierarchy (Level 0, or L[0]) represents the overall goal of determining how drought is apt to affect water supplies. Immediately below it, at L(1), would be different drought scenarios. These scenarios would distinguish droughts of different magnitudes and embody characteristics meaningful to water-resource managers, such as duration and degree of dryness. Level 2 would show the effects of droughts of different severities on the input of water from the natural hydrological system to the supply system. Such effects could be represented by quantitative estimates, expressed as ranges, of the degree to which the predrought input might be altered under a given climatic scenario. In turn, L(3), would depict the effects of those changes upon the final supply availability. The demand hierarchy corresponding to each demand area would consist of analogous levels. Level 1 would represent the climate scenarios, L(2) the sectors or uses (e.g., agriculture) likely to be affected, and L(3) the quantitative estimates of the relative changes in water demand by the preceding sectors.

Following AHP convention, the elements at each level in the hierarchy would be prioritized by comparing them pairwise with respect to relevant elements at the next higher level (Saaty 1980). At L(1) of a given supply hierarchy, for example, we would ask, "How much more likely is climatic scenario i than scenario j?" If groundwater is an important source, the assessment question at L(2) might be: "Under scenario i, how much more (less) likely is it that infiltration would be reduced by 5 to 10% than from 10 to 15%?" Finally, the L(3) elements would be compared thus: "Given that scenario i results in the decline of infiltration by 10 to 15%, how much more likely is the reduction in sustainable yield (relative to a given hydraulic head) to be between 0 and 5% than between 5 and 10%?" Summing these final priorities yields the area's estimated percentage change in supply for the planning period.

The queries pertaining to each demand hierarchy are somewhat different. After comparing the scenarios at L(1) with respect to likelihood, sector m is compared to sector n at L(2) according to the amount of water consumed by each under *nondrought* conditions. Since the assessments are made relative to only one situation, they will be identical for all reference scenarios at L(1). If use data are available, direct assessments may be used; otherwise, one asks, "How much more (less) water is (typically) consumed by sector m than sector n under nondrought conditions for this time of year?" The result is a weight for each sector in proportion to its "normal" (nondrought) water usage. In contrast to the comparisons at L(2), those at L(3), assessing the relative likelihood of each demand-modification factor, do distinguish among climatic scenarios: "Under climatic scenario i, how much more (less) likely is it that sector m's demand will rise between 5 and 10% than between 10 and 15%?" Summing these final priorities yields the estimated percentage change in the study area's total demand. Multiplying this demand-modification factor by the nondrought use gives the area's new demand for the target period, corresponding to a demand node in Figure 77b.

Assessing Drought Likelihood. Drought scenarios appear at L(2) in the demand and supply hierarchies discussed earlier, and the statistical characterization of drought can be used to aid the assessment of the likelihood of such scenarios. Two tasks are required, the specification of a scenario and the estimate of its probability.

Drought scenarios are defined by first specifying a period of interest and then a small number of values of a selected drought attribute. Given k such values, k+1 scenarios will be defined, each scenario corresponding to a drought condition falling between two adjacent values. For example, at the end of June a water manager might be interested in the likelihood of drought in July and the consequent increased demand for irrigation water. If a minimum of 30 mm of rain were required during July in order to avoid losses to the crop in question, the manager could specify precipitation (P) as the drought attribute and one meaningful value equal to 30 mm, i.e., $P_1 = 30$. With that single value, two scenarios would be defined, one with rainfall less than 30 mm and the other with 30 mm or more. If another value were also specified, such that $P_2 = 20$, then three scenarios would be defined: when $P \leq 20$, when $20 < P < 30$, and when $P \geq 30$. Although in this example the attribute is precipitation, many others are possible; a drought index, such as the Palmer Drought Severity Index, would be one. Likewise, one may prefer to specify rainfall amounts in terms of return periods rather than in depth.

Once scenarios are defined and specified, two basic approaches to estimating their probabilities may be employed. One way calculates the probabilities of each scenario in the future period of interest based on the frequency of that condition during the period of record. For example, consider once again that July is the period of interest, that precipitation amount P_1 is the chosen attribute value, and that n is the number of consecutive years of precipitation record. Then if P_1 has been exceeded m times during the period of record, the probability that P_1 will be exceeded in July can be taken as m/n; that is, $Pr(P_{July} > P_1) = m/n$. (Hydrologists usually slightly modify this formula to obtain a "plotting position," but the concept remains the same.) This approach is simple to use, but it ignores the history of the current drought, since it assumes that the probability of exceeding or falling below the attribute value in July is independent of the values obtained for that attribute in the immediately preceding months.

If one believes that an attribute's value for a given period of interest depends significantly upon such values for previous periods, then one should incorporate available information on those values as well. Guidance on how to do this comes from a well-known relationship in probability theory,

$$Pr(AB) = Pr(A|B) \times Pr(B) = Pr(B|A) \times Pr(A) .$$

Continuing with the same example, let event A be precipitation in July of P_1 or greater. Similarly, let event B refer to the amount of precipitation received in some period of interest prior to July, say June. More precisely, let B represent amount of precipitation in June equal to or less than P_0. Assuming that A is dependent on B, one would like to estimate the joint probability of the two events, Pr(AB). Since B has already occurred, its probability is 100% and $Pr(B) = 1.0$. Thus, all that is needed is an estimate of the conditional probability Pr(A|B).

To estimate Pr(A|B), one first identifies the years of record in which the corresponding "preceding period" (e.g., June) received precipitation of P_0 or less. Suppose there are j such years, $j \leq n$. One then determines how many of those years registered precipitation of P_1 or more. If there were i of them, then the conditional probability of getting precipitation at least equal to P_1 is i/j; for this example:

$$Pr(A|B) = Pr(P_{July} \geq P_1 \mid P_{June} \leq P_0) = \frac{i}{j} .$$

The decision to use simple probabilities implies the belief that the future period of interest is independent of previous periods. The use of conditional probabilities implies those events are dependent. These mark the two ends of the continuum, since the less the independence the closer to the "conditional" end the true probability would lie, and vice versa. But one does not know with certainty what the degree of dependence is, and it will vary with the attribute used, the region, and the months of interest. Therefore, in estimating the likelihood of a given scenario, the water manager may specify a probability different from either of these yet based on (i.e., informed by) both. The importance given to the conditional probability reflects the degree of persistence the manager feels to be represented in the index used.

Determining a New Allocation. Given the estimated effects of drought on supplies and demands, how should the current allocation of water be modified? Assuming the social acceptability (if not optimality) of the existing allocation, and that some cut in demand is necessitated (or merely desirable—e.g., for aquifer management), a common approach is simply to spread any necessary reduction evenly, in percentage terms, across all users. Such a "proportional rollback," however, does not consider the distribution of drought impacts, either upon supplies or upon demands. Modifying the supplies and demands by the factors determined by the AHP procedure just described, however, does indeed consider such impacts. If one now wishes to reallocate the resource in an optimal manner, considering these anticipated changes in supplies and demands, a constrained optimization model such as the following may be employed.

Let x_{ijk} represent the amount of water in millions of gallons per day (mgd) that water-supply system j will get from source i and provide to user k. Also, denote by S_i the available supply (mgd) at source i, and by D_k the demand (mgd) by user k. In addition, let C_{ij} be the transfer capacity (mgd) between source i and system j, and C_{jk} the transfer capacity between system j and user k. Then in times of shortage any allocation must meet the following conditions.

1. Water provided to some supply system cannot exceed source capacity:

$$\sum_j x_{ij} \leq S_i \qquad \text{for all i, i = 1, 2,..., n} \tag{1}$$

2. Water entering system j from source i either supplies users k or is stored within system j:

$$\sum_i x_{ij} - \sum_k x_{jk} \geq 0 \qquad \text{for all j, j = 1, 2,..., m} \tag{2}$$

3. Water transfer between sources and supply systems cannot exceed limits on transfer rate:

$$x_{ij} \leq C_{ij} \qquad \text{for all (i,j) links} \tag{3}$$

4. Water transfer by the supply system to users must not exceed system limits on the rate of such transfer:

$$x_{jk} \leq C_{jk} \qquad \text{for all (j,k) links} \qquad (4)$$

5. Determine the deficit d_k between user k's demand and the amount received:

$$\sum_j x_{jk} + d_k = D_k \qquad \text{for all } k,\ k = 1, 2, \ldots, s\ . \qquad (5)$$

Except for a slight variation in Equation (5), the preceding constraints are those comprising the well-known transshipment problem in linear programming. Equation (5) differs from the standard formulation in that, due to the supply shortage, it is not required to meet all demands.

In the transshipment problem, the objective is usually to minimize the total cost of the distribution. Here, we can think of minimizing at least two different costs. One refers to the monetary (financial) cost associated with the physical transfer of the water. Letting c_{ij} denote the cost of moving 1 mgd between source i and supply system j, and c_{jk} that between the supply system and user k, the objective would be to minimize COST:

$$\sum_i \sum_j c_{ij}x_{ij} + \sum_i \sum_j c_{jk}x_{jk} - \text{COST} = 0\ . \qquad (6)$$

Another cost is that incurred by society at large, including that corresponding to the individual user, when supplies fall short of demands. Hence, another objective is to minimize DEFICITS, the sum of weighted deficits:

$$\sum_k w_k d_k - \text{DEFICITS} = 0\ . \qquad (7)$$

The weights w_k signify that a unit shortfall from one user's demand does not necessarily represent the same cost, or importance, to society (or to that user) as does a similar shortfall from another user's demand. Weights can thus be assigned to reflect these different costs if so desired.

AN ILLUSTRATIVE EXAMPLE. To illustrate the overall procedure, let us consider a simplified example patterned after and reflecting in a general sense the situation found on the island of Maui. Since some of the data used here are hypothetical, the quantitative dimension should be viewed as illustrative only.

Drought's Impacts on Supply and Demand. The first step is to structure analytic hierarchies to estimate drought effects upon water supplies and demands. Figure 78 shows a hierarchy corresponding to changes in available water supply in one source area, that of the ʻĪao System. The month of April was selected as the period of interest, and four drought scenarios were defined by return period: an "extreme drought" is one that would occur no more often, on average, than once in 20 years; a "bad drought" corresponds to one more frequent than an extreme drought but still likely to occur no more often than once in 10 years; a "mild drought" has an expected return frequency not exceeding once every 5 years but more often than the

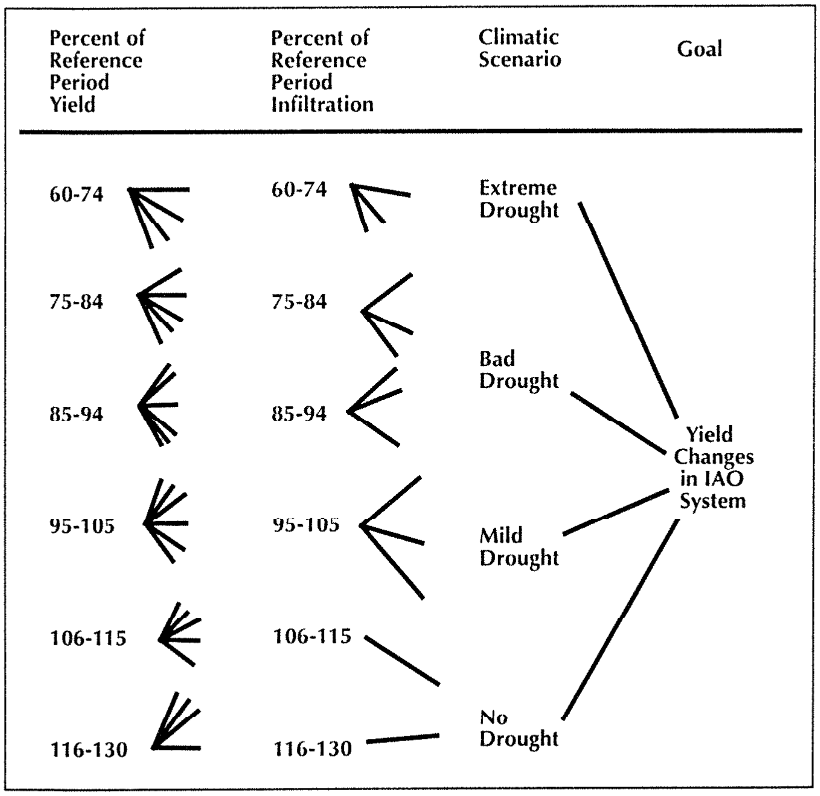


Figure 78. Hierarchy to estimate changes in water yield

more severe droughts; and "no drought" refers to all other cases. Probabilities of these scenarios are respectively then, 5, 5, 10, and 80%.

Infiltration-modification factors covered intervals ranging from 0.60–0.74 to 1.16–1.30. Higher factors were included in the comparisons under the "no-drought" scenario, while lower ones were compared for more severe droughts. Finally, the yield-modification factors chosen for the evaluation ranged from 0.60 to 1.30. Table 34 shows the final ("global") priority estimated for each yield-factor interval.

The hierarchy corresponding to changes in water demand in the Wailuku-Kahului Community Plan Area is shown in Figure 79. The drought scenarios in L(1) were defined as in the supply hierarchy, but since this area is not coincident with that of the ʻĪao System, the actual precipitation amounts to which they refer are different. Six different uses are distinguished at L(2): interior and exterior uses for each of the domestic (residential), commercial (including tourist facilities and resorts), and public sectors. In this example, agricultural uses were omitted since the focus is on municipal water allocation. Seven demand-

TABLE 34. LIKELIHOOD WEIGHTS FOR YIELD-MODIFICATION FACTORS FOR 'ĪAO, MAUI, WATER SOURCE

Factor Interval	Mid-Point	Likelihood Weight
0.95–1.05	1.00	0.242
1.06–1.15	1.10	0.224
0.85–0.94	0.90	0.173
1.16–1.30	1.23	0.155
0.75–0.84	0.80	0.127
0.60–0.74	0.67	0.079

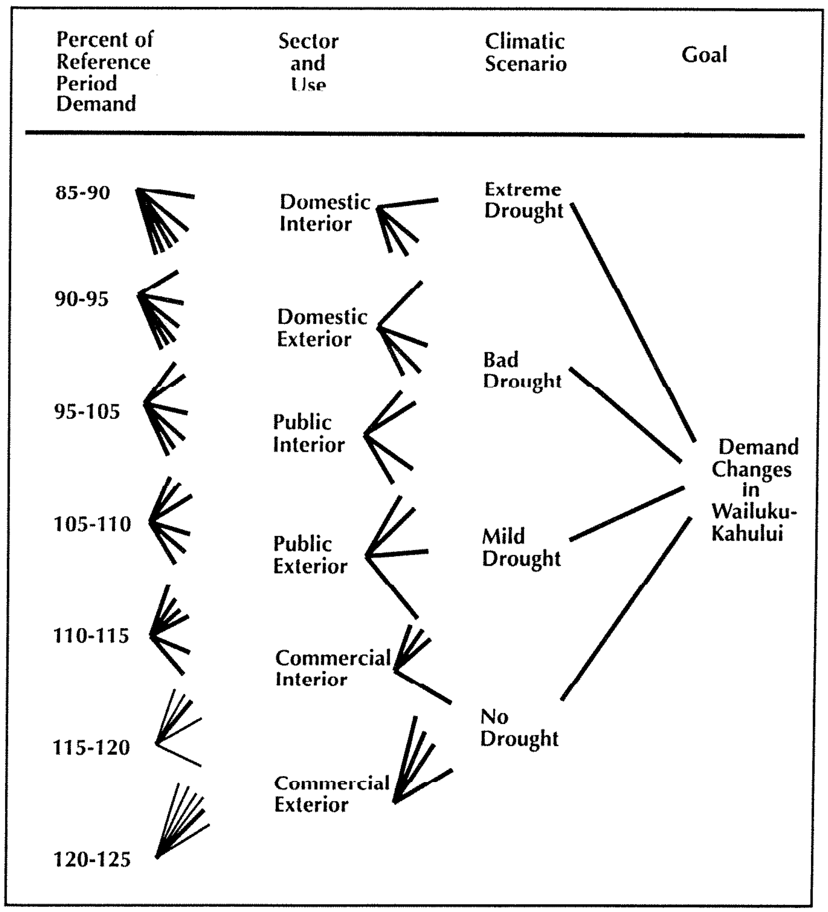


Figure 79. Hierarchy to estimate changes in water demand

modification-factor intervals comprise the alternatives at L(3). Table 35 indicates their global relative weights.

Figures 78 and 79 illustrate respectively the hierarchies for only one supply and one demand area. On Maui, there are 25 such "systems" comprising the six source sectors in the groundwater classification currently being followed. Similarly, Wailuku-Kahului is only one of six Community Plan Areas. Each of these would require its own hierarchy and associated assessments.

The Water Allocation Model. To illustrate how the prioritized yield- and demand-modification factors can be used to help determine an "optimal" water allocation at the onset of a drought period, consider a situation in which eight source areas must supply six demand regions. Table 36 shows each source's available supplies at the end of March, the consumption of the demand areas at that time, and the sources capable of supplying each demand region. With all variables in units of mgd, and assuming no intermediate water-supply systems and the single objective of minimizing equally-weighted deficits, the standard transportation (rather than transshipment) model can be used. The optimal allocation under this situation allows all deficits to be met while leaving excess capacity at the 'Īao, Ukumeha, and Kipahulu sources (Table 37, col. 2 and 3). This allocation will now be considered the reference condition, as though it were the predrought allocation.

Now the modification factors determined via the AHP come into play. Using the midpoint of each modification-factor interval, multiplying it by the weight of that interval, and summing the products, one obtains the weighted-average yield-modification factor for the 'Īao source area; in this case, it is 0.989. Multiplying this by the end-of-March capacity for 'Īao, 13.11 mgd, one gets 12.97 mgd, the estimated availability for April. By a similar procedure, the weighted average for the Wailuku-Kahului Community Plan Area is 1.012, which, when multiplied by the end-of-March consumption figure for that region (7.66 mgd), yields 7.75 mgd as its projected April demand. Following the identical procedure for all source and demand regions results in new limits and demands (Table 37, col. 4).

Modifying the supplies and demands in the reference allocation to reflect these estimated changes yields a new model, Model I. The optimal allocation under this model would leave 'Īao as the sole source with excess supply, and deficits would occur in Lahaina, Kula, and Hāna (Table 37, col. 5).

While the single objective in Model I is to minimize equally-weighted deficits, that in Model II attempts to minimize the total cost of water transfer as well. Including cost coefficients (arbitrary, in this case) in Equation (6), putting COST in the objective function alongside DEFICITS, and varying the objective-function coefficients, one can now explore the

TABLE 35. LIKELIHOOD WEIGHTS FOR DEMAND-MODIFICATION FACTORS FOR WAILUKU-KAHULUI, MAUI, COMMUNITY PLAN AREA

Factor Interval	Mid-Point	Likelihood Weight
0.95–1.05	1.000	0.345
1.05–1.10	1.075	0.212
0.90–0.95	0.925	0.169
1.10–1.15	1.125	0.150
0.85–0.90	0.875	0.112
1.15–1.20	1.175	0.008
1.20–1.25	1.225	0.005

TABLE 36. SOURCES, DEMAND REGIONS, SUPPLIES, DEMANDS, AND SOURCE-DEMAND LINKS FOR PRE-DROUGHT ALLOCATION SITUATION

SUPPLY (mgd)	SOURCE NAME	SOURCE No.	POSSIBLE DEMAND REGION*					
			A	B	C	D	E	F
13.11	Iao	1	*	*		*		
2.20	Waihee	2	*	*				
6.00	Ukumeha	3		*	*			
2.80	Launiu	4			*			
1.10	Makawao	5				*	*	
3.85	Honopou	6				*	*	*
1.00	Kipahulu	7				*	*	
0.07	Keane	8				*		*
0.28	Demands (mgd):		7.66	7.08	8.76	0.95	4.77	

*A = Wailuku; B = Kihei; C = Lahaina; D = Paia; E = Kula; F = Hana.

consequences of assigning different priorities to the objectives. When both have coefficients of 1.0, the results are as shown in Table 37 (col. 7).

The differences between the solutions to Models I and II demonstrate that the best allocation depends on the objectives being considered and the weight given them. They also point up the importance of how an objective is defined and measured: there is no *a priori* reason, for example, why all deficits should be assumed of equal consequence.

CONCLUSION. Making decisions regarding the allocation of water under scarcity is often complex and always value-laden. In areas normally blessed with sufficient water to meet demands, the occurrence of drought frequently requires hasty allocation decisions to be made without the benefit of a well-reasoned procedure to guide them. A common practice is to

TABLE 37. SUPPLIES, DEMANDS, EXCESS SUPPLIES, AND DEFICITS FOR OPTIMAL ALLOCATION UNDER EACH MODEL EXAMINED

Supplies:	REFERENCE		MODEL I		MODEL II	
SOURCE	Limit	Excess	Limit	Excess	Limit	Excess
Iao	13.11	0.57	12.97	0.25	12.97	5.32
Waihee	2.20	0.00	2.15	0.00	2.15	0.00
Ukumeha	6.00	0.04	6.00	0.00	6.00	0.00
Launiu	2.80	0.00	2.71	0.00	2.17	2.17
Makawao	1.10	0.00	1.02	0.00	1.02	1.02
Honopou	3.85	0.00	3.79	0.00	3.79	3.46
Kipahulu	1.00	0.02	1.00	0.00	1.00	1.00
Keane	0.07	0.00	0.06	0.00	0.06	0.00

Demands: Demand Region	Demand (mgd)	Deficit	Demand (mgd)	Deficit	Demand (mgd)	Deficit
Wailuku	7.66	0.00	7.75	0.00	7.75	0.00
Kihei	7.08	0.00	7.12	0.00	7.12	0.00
Lahaina	8.76	0.00	8.83	0.12	8.83	8.83
Paia	0.95	0.00	0.99	0.00	0.99	0.00
Kula	4.77	0.00	4.91	0.03	4.91	4.91
Hana	0.28	0.00	0.33	0.33	0.33	0.00

require across-the-board cuts in consumption which are percentage-wise equivalent. Such a practice is arbitrary and, notwithstanding its proportional equality, is neither equitable nor efficient.

The approach presented here alleviates such arbitrariness and simultaneously reveals the values employed in the allocation decision. Beginning with the supply capacities and demands prior to water shortage, the procedure uses empirical data on the relevant hydrological systems and consumption patterns, together with one's judgment, to estimate changes to supplies and demands which are likely to occur during a future period. The future period is characterized by a set of climatic scenarios whose probabilities may be based in part on the historical record. Once the likely changes are determined, multiobjective optimization is used to identify an allocation which best corresponds to one's view of the relative importance of the objectives and the way in which they are defined.

Drought and the Selection of Water-Supply Projects

INTRODUCTION. Projects to improve water-supply systems may be designed to meet any of several possible needs. The aim may be to augment average or maximum daily water-delivery capacity to expand the service area. Since demand for water commonly does not coincide with its natural availability, another common goal is that of increasing the reliability of supply. And, lest we forget the porkbarrel of the American West, projects may be conceived of largely in terms of their political payoffs. Of course, projects need not be confined to only one of these goals, but may address several simultaneously. To one degree or another, then, water-supply projects clearly contribute, positively or negatively, to multiple objectives.

This section treats the consideration of such multiple objectives in the evaluation and selection of a set of water-supply projects, focussing on drought and its explicit incorporation into a selection procedure. As part of this, it will be shown that how drought is defined, as well as one's attitude toward risk, influences the weights given the different objectives to which a project contributes. These weights, in turn, determine the priorities accorded the projects under consideration. By extension, decisions on project selection, far from being purely technical in basis, will be seen to encompass values and hence to be ultimately political. Methods that can take account of these aspects of the water-project selection problem should be preferred over those that cannot.

The two-stage procedure described here has these capabilities. First, a multiattribute value model is used to evaluate the overall worth of each project in terms of four principal criteria. The values thus obtained are then used as the objective-function coefficients in an integer program whose constraints represent available budget and project interdependencies. The procedure is illustrated in an example adapted from a water-supply plan for part of the island of Maui (Department of Water Supply n.d.).

GUIDELINES FOR A PROJECT-SELECTION PROCEDURE. Three sets of questions need to be answered to evaluate a group of proposed projects with respect to a set of water-supply objectives. First, how important is each of the objectives? This may depend on how well the existing water-supply system presently meets such goals, as well as on how the system's wider environment might change in the future. Two obvious elements of that environment are the demand for water and its available supply. Second, to what degree does each project by itself contribute to the achievement of each objective? Third, considering resource constraints and project interaction, how should one evaluate the worth of subsets of the entire group of candidate projects?

Answers to these questions help one to decide which projects should be implemented, although they do not themselves determine that selection. For example, the selection philosophy may aim to *optimize* the water-supply system in accord with criteria pertaining to system performance. Projects might then be selected to maximize the total contribution of all projects together, taking into account limits on budget and other resources required for project development. This is the case discussed here. Yet policy may be more concerned with the system's capacity to meet the challenges of a highly uncertain environment, in which instance adequate performance under a wide range of conditions and ease of modification might take precedence over optimization as conventionally understood. Such a concern, implying *satisficing* and *evolutionary* philosophies, is treated elsewhere.

In the context of the optimization approach, one can identify several desirable characteristics of any procedure designed to aid in the selection of water-supply projects. One should be able to use results from statistical and other empirical studies of hydrological systems to help predict future changes in water demand and availability. However, where there is inadequate data on such systems, or a lack of confidence in or misunderstanding of statistical analyses, there is a need to be able to complement such studies with personal judgment based on experience or other subjective factors. (Indeed, some [e.g., von Winterfeldt and Edwards 1986] argue that the preferred way to represent all uncertainties is as probabilities based on personal judgments of likelihoods of the corresponding real-world events.) Furthermore, since any prediction will be uncertain, and the relative importance accorded any particular water-supply goal will be subjective, one should be able to examine the sensitivity of the projects' priorities to changes in such factors. Finally, to allow the allocation of project-development resources, the procedure should be able to incorporate constraints on such resources, and priorities should be determined on a ratio scale.

PROJECT SELECTION MODEL. The procedure described below meets the foregoing desiderata and is comprised of two main parts. First, the analytic hierarchy process (AHP) (Saaty 1980, 1982) is used to establish project priorities. It begins by decomposing the selection problem into a value tree (analytic hierarchy) with levels representing the overall goal, drought scenarios, water-demand scenarios, criteria, subcriteria, and individual candidate projects. Using paired comparisons and assuming an additive multiattribute value function, it then employs the eigenvector method to estimate ratio-level weights that represent project priorities. An elementary exposition of the AHP is given in Appendix C. The second part is an optimization model that identifies the set of projects that will maximize the projects' aggregate contribution to meeting the overall goal subject to budget and other constraints.

Analytic Hierarchy. The approach will be illustrated with reference to the water-supply system shown in Figure 80 and the set of projects representing potential additions to it, listed in Table 38. Figure 81 shows the hierarchy of scenarios, criteria, and candidate projects used to derive the priorities. The overall goal, at the apex of the hierarchy, is to rate the individual projects according to their potential improvement to the water-supply system. The first level below the apex—referred to as L(1)—displays three different drought scenarios, and under each of those are three different scenarios of growth in water demand. At L(3) are four criteria by which a project's worth may be evaluated. The L(4) subcriteria represent the different

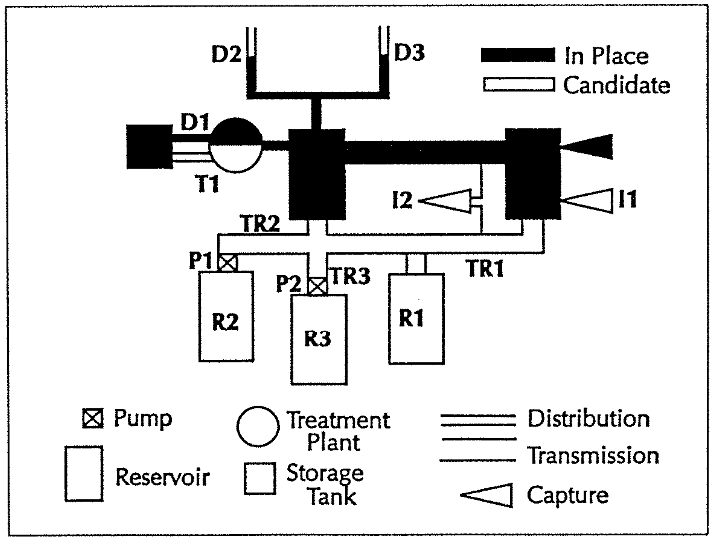


Figure 80. Structure of existing water-supply system and relationship to candidate projects

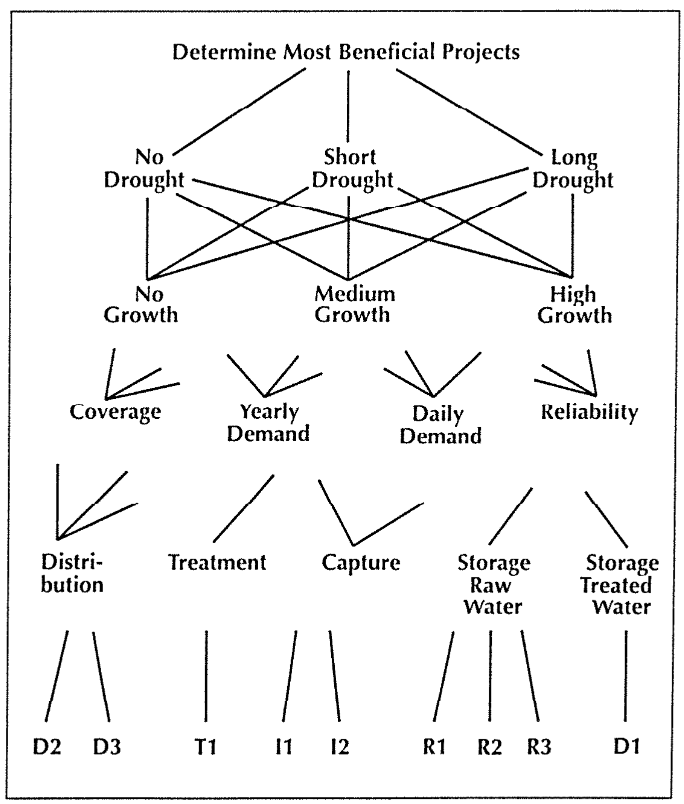


Figure 81. Analytic hierarchy showing drought and water-management scenarios, criteria, subcriteria, and project alternatives

TABLE 38. CANDIDATE PROJECTS TO IMPROVE WATER SYSTEMS

Project ID	Description
D1	11,500 ft 16 in. transmission line
D2	2,000 ft 6 in. distribution line
D3	4,800 ft 6 in. distribution line
I1	Repair intakes
I2	Fix intakes and 2,115 ft 24 in. transmission line
R1	100 million gallon (mil gal) reservoir
R2	50 mil gal reservoir
R3	75 mil gal reservoir
T1	Expand treatment plant to 2.5 mgd
TR1	17,000 ft 36 in. transmission line
TR2	6,000 ft 24 in. pipeline
TR3	3,000 ft 24 in. transmission line
P1	Pump from reservoir R2 to treatment plant
P2	Pump from reservoir R3 to treatment plant

water-supply functions which a project may perform and which contribute to the achievement of the four goals at L(3). Below these functions are the candidate projects themselves.

Sets of comparisons are required with respect to every element—the "parent" nodes—at levels 0 through 4. Pairwise comparisons of drought scenarios at L(1) with respect to the overall goal at L(0) are made in terms of likelihood: how much more likely is drought scenario 1 than drought scenario 2? Scenarios may be defined in any way relevant to the problem. For this example, they were identified in terms of the length of regional drought events as defined according to the Bhalme and Mooley Drought Index and described in detail elsewhere. With the duration of the minimum drought lasting two months, a *Short Drought* is defined here as one of two to five months' duration, and a *Long Drought* as one lasting six months or more. All other conditions are termed *No Drought.*

Three different scenarios are considered for growth in water demand, expressed by the elements at L(2). *No Growth* refers to an annual growth rate not exceeding the average during the previous five years, *Medium Growth* to a rate falling between 1 and 2 times that average, and *High Growth* to a rate greater than these.

The four goals of the water-supply system at L(3) are defined thus:

1. *Daily Demand*—to meet peak hourly demand, measured in average flow during a specific hour, on all days of the year;
2. *Yearly Demand*—to meet total demand over the entire year, measured in total volume;
3. *Coverage*—to extend service to all potential customers in the region; and

4. *Reliability*—to eliminate supply unreliability, measured as the sum of daily demand-over-supply differences throughout the year.

The elements at L(4) are conventional terms for the principal functions of the different components of a water-supply system, functions which contribute directly to the preceding criteria. *Distribution* refers to the conveyance of treated water to the ultimate consumers. Aside from their obvious contribution to the *Coverage* objective, distribution lines also contribute to *Yearly Demand* and *Daily Demand* by meeting the portion of these demands exerted by the consumers the new lines (will) serve. *Treatment* and *Treated-Water Storage* facilities help meet *Daily Demand* since maximum hourly throughput depends on the flows emanating from these two types of sources. *Capture* facilities, such as intakes and their associated pumps, not only add to the total amount of water made available during the year, contributing to *Yearly Demand*; they also support the *Reliability* goal, since under drought additional intakes can extract water from new sources and help to relieve a deficit without adding to the total yearly supply. Finally, a major purpose of *Raw-Water Storage* facilities, such as reservoirs, is to enhance the reliability of supply.

"Transmission," referring to the conveyance of water from point of capture to a raw-water storage facility or directly to the treatment plant, does not appear at L(4) since by itself it contributes nothing to any of the L(3) objectives. That it may be required for other components to function is undeniable, and such requirements are taken care of in the optimization model.

Policies and Assessments. Pairwise comparisons required by the AHP were made with respect to all parent nodes, beginning at the bottom of the hierarchy and working up, level by level. The assessments of projects relative to L(4) functions, and of those functions with respect to the L(3) criteria, constitute effects, or impact matrices. The scores in these matrices are not merely the ratios of impact scores in terms of natural units, but rather ratios of the value or worth of such consequences. Although such valuation makes it clear that these assessments are not objective, they are more easily agreed-upon than the preference and likelihood assessments, which are more overtly value-laden, needed higher up.

Comparisons of elements at L(1), L(2), and L(3) were made for all combinations of three different policies; with two variants for each policy, eight different cases were modeled. In general, the greater the expected rise in water demand, the greater the importance given the two *Demand* criteria. Likewise, expected increases in drought probability and/or length were accompanied by increased importance given to *Reliability*. Otherwise, assessments depended on the combination of policies in effect. Policies pertain to criterion (goal) preferences, drought-scenario likelihoods, and the relationship between drought scenario and water-demand management. The distinctions in each area can be summarized as follows.

Criterion Preferences:

C1. Growth Policy. Emphasis is on meeting growth in water demand. *Demand* and *Reliability* are preferred over *Coverage*. *Reliability* is slightly preferred over *Demand* in *Short Drought/Medium Growth* and *Long Drought/High Growth* scenarios.

C2. Current Demand Policy. Emphasis is on providing good service to existing customers and to serve potential customers (e.g., households, commercial establishments) already resident in the service area but currently lacking service. *Coverage* is heavily emphasized over *Demand* and at least as preferred as *Reliability*. *Reliability* is at least as preferred as *Demand*.

Drought Likelihood:

D1. Frequency Based. Drought is defined as "climatic" drought, characterized entirely by climatic attributes, and is measured with respect to relative frequencies of drought events. The probabilities used are *No Drought*, 75%; *Short Drought*, 20%; *Long Drought*, 5%.

D2. Judgmentally Based. Drought probabilities reflect personal appraisals of recurrence likelihood. Drought is an amalgam of climatic attributes and the effects of these on economic, social, and agricultural systems. Events in the distant past are heavily discounted relative to more recent ones. Recent attention to possible global warming results in equal probability being assigned to each scenario.

Drought and Demand Management:

M1. No Relation. Drought likelihood is expected to have no influence on demand-management policies. *Medium-Growth* and *High-Growth* scenarios are considered of equal likelihood and are significantly more likely than the *No-Growth* case.

M2. Direct Influence. The higher the expected likelihood and length of drought, the stronger will be policies that attempt to inhibit growth in water demand.

Thus, comparisons at L(3) (with reference to L(2) elements) were made under four different circumstances of drought and demand management (D1-M1, D1-M2, D2-M1, D2-M2), and those comparisons were made in two different ways (C1, C2). The comparisons were in terms of preference, responding to questions of the type: "Given a long drought and a medium growth rate in water demand, is it more important to meet peak daily demand or to expand coverage?" These assessments implicitly reflect one's attitude toward risk. For example, two people may assign different levels of importance to reliability even though they entirely agree on the drought probabilities.

The priorities resulting from the comparisons for each of the eight cases, as calculated by the eigenvector method, are shown in Table 39. Inspection of the table reveals changes not only in cardinal priorities but also in the rankings of the projects, although in many cases the

TABLE 39. PROJECT PRIORITY WEIGHTS DERIVED BY AHP VALUE MODEL FOR EACH COMPOSITE SCENARIO

PROJECT	D1 (FREQUENCY-BASED DROUGHT)				D2 (JUDGMENT-BASED DROUGHT)			
	C1-M1 Wt	C1-M2 Wt	C2-M1 Wt	C2-M2 Wt	C1-M1 Wt	C1-M2 Wt	C2-M1 Wt	C2-M2 Wt
D1	0.079	0.079	0.031	0.025	0.097	0.077	0.038	0.030
D2	0.238	0.262	0.379	0.498	0.153	0.171	0.389	0.422
D2	0.229	0.189	0.228	0.232	0.156	0.143	0.185	0.220
I1	0.074	0.076	0.073	0.045	0.058	0.060	0.045	0.033
I2	0.141	0.140	0.143	0.090	0.171	0.167	0.117	0.093
R1	0.059	0.061	0.046	0.036	0.171	0.177	0.118	0.105
R2	0.017	0.019	0.016	0.012	0.034	0.042	0.023	0.024
R3	0.030	0.032	0.026	0.020	0.069	0.077	0.048	0.045
T1	0.134	0.142	0.057	0.042	0.090	0.085	0.037	0.028

<u>Policy on Water Demand</u>
C1: Growth-Oriented
C2: Current-Demand Oriented

<u>Drought and Demand Management</u>
M1: No Relation
M2: Direct Influence

changes are so small as to seem insignificant. For example, under cases of relatively infrequent drought (D1) and constant criterion preferences—i.e., comparing C1-M1-D1 with C1-M2-D1, and C2-M1-D1 with C2-M2-D1—changes in demand-management policy result in only one change in project rankings, and the difference in priorities is numerically marginal. Neither does demand management have any effect on project rankings when drought likelihood is high (D2) and the satisfaction of current demand is emphasized (C2). Considerable differences do result, however, when management policies or criterion preferences change in conjunction with changes in drought-likelihood assessment, e.g., the difference between C2-M2-D1 and C2-M1-D2, and between C1-M2-D1 and C2-M2-D2. Thus, one's views about the likelihood of drought (and by extension what constitutes drought), the relative importance of each of the water-supply goals, and the type of demand-management policy to invoke, all value-laden questions, clearly have the potential to affect project selection.

In addition to their use in ranking the projects, the AHP-derived priorities (weights) also measure the benefit (assuming the goals used are sufficient in this regard) to be derived from each project. Dividing a priority by the corresponding project's cost is a measure of efficiency analogous to a benefit-cost ratio. If there were no resource (e.g., budget) constraints, benefits would be maximized by ordering the projects according to this ratio and simply selecting the top one on the stack when conditions warranted a new project. With resource constraints, however, such a procedure does not guarantee maximum benefits, and optimization is required.

Project Selection. Integer programming was used to determine which set of projects to implement to derive maximum total benefits. The potential benefits of each project were represented by the project's priority, and constraints were of two main types: those pertaining to resource availability and those corresponding to interdependence conditions among the projects themselves. Considering budget limits as the only resource constraint, the following model will identify the optimal set of projects for any budget level.

Maximize benefits B,

$$B = \sum_j P_j X_j \tag{1}$$

subject to

$$4300\ TR1 + 80\ I1 + 420\ I2 + 1000\ D1 + 13000\ R1 + 127\ D2 + 315\ T1 + 5400\ R2 + 1000\ TR2 + 50\ P1 + 301\ D3 + 12000\ R3 + 700\ TR3 + 50\ P2 \leq \text{budget} \tag{2}$$

$$TR1 \leq R1 + R2 + R3 \tag{3}$$

$$R1 \leq I1 + I2 \tag{4}$$

$$R2 \leq I1 + I2 \tag{5}$$

$$R3 \leq I1 + I2 \tag{6}$$

$$D1 \leq T1 \tag{7}$$

$$R1 + R2 \leq I1 + I2 \tag{8}$$

$$R1 + R3 \leq I1 + I2 \tag{9}$$

$$R2 + R3 \leq I1 + I2 \tag{10}$$

$$I1 + I2 - TR1 \leq 1 \tag{11}$$

$$I1 + I2 - R1 - R2 - R3 \leq 1 \tag{12}$$

$$TR2 = R2 \tag{13}$$

$$P1 = R2 \tag{14}$$

$$TR3 = R3 \tag{15}$$

$$P2 = R3 \tag{16}$$

$$X_j = 1, \text{ if project } j \text{ is selected}, \quad = 0, \text{ otherwise}. \tag{17}$$

The X_j in expression (1) represent the variables in exps. (2) to (16) and refer to the projects listed in Table 38. The P_j in exp. (1) represent their AHP-derived priorities (Table 39). Notice that P_j is nonzero only for the projects appearing in the analytic hierarchy, i.e., those in Table 39. The coefficients in the left-hand side of exp. (2) are the costs of the corresponding projects, and their sum cannot exceed the budget available.

Expressions (3) to (16) represent the dependencies among individual projects. Exp. (3) states that transmission line TR1 may be added only if at least one reservoir is constructed. Exps. (4) to (6) together require additional capture (right-hand side) before new reservoirs (left-hand side) can be added. Exp. (7) requires expansion of the treatment plant (T1) before an additional conveyance line (D1) to the storage tank is built. Exps. (8) to (10) together require both capture projects (right-hand side) to be selected before two or more reservoirs may be added. In exp. (11), transmission line TR1 must be added if both intake projects I1 and I2 are chosen. Exp. (12) states that if both I1 and I2 are selected, then at least one of the three reservoirs must be built. Exps. (13) to (16) require that the condition of the projects on the left-hand side (chosen/not chosen) be the same as that for those on the right-hand side.

Substituting for P_j the priorities corresponding to one of the eight cases and the projects in Table 38 for the X_j in exp. (1), and selecting a budget level of interest for exp. (2), one may solve exps. (1) to (17) to identify the optimal project package corresponding to that situation. Surprisingly, of the higher budget levels examined, the optimal set is identical for all eight cases, varying only with the budget limit (Table 40). For the budget limits below $20 million that were examined, however, differences in optimal project packages do indeed surface. Table 41 shows the results for a budget of $19 million. For the budget levels examined, the optimal packages are identical for all cases characterized by infrequent drought (D1). When drought likelihood is considered higher (D2), it is the criterion preference (C1 vs. C2) that effectively determines the optimal set of projects.

These results demonstrate clearly the effect that alternative estimates of drought likelihood and goal priorities can have on infrastructure evaluation. In addition to the probability estimation process itself, different estimates of drought likelihood can arise from different conceptions of drought (e.g., agricultural vs. climatic) as well as from the selection of different climatic attributes or the use of different thresholds for those selected. Differences in drought-scenario probabilities and goal priorities can result entirely from being assessed by different people: a long-time resident may base his estimation of drought recurrence probabilities on his past experience, while an engineer might prefer a statistical analysis of rainfall records; an aquatic biologist may define drought according to streamflow but a climatologist might focus on rainfall; a land developer might give considerable weight to increasing the capacity of the water-supply system, whereas farmers might prefer efforts aimed at improving reliability.

TABLE 40. OPTIMAL SET OF PROJECTS FOR ALL CASES

BUDGET $\$10^6$	PROJECTS													
	D1	D2	D3	I1	I2	R1	R2	R3	T1	TR1	TR2	TR3	P1	P2
20	x	x	x	x	x	x			x	x				
25	x	x	x	x	x	x			x	x				
30	x	x	x	x	x	x	x		x	x	x		x	
35	x	x	x	x	x	x		x	x	x		x		x

TABLE 41. OPTIMAL SETS OF PROJECTS FOR $19 MILLION BUDGET

CASE	PROJECTS													
	D1	D2	D3	I1	I2	R1	R2	R3	T1	TR1	TR2	TR3	P1	P2
C1-M1-D1	x	x	x	x	x		x		x	x	x		x	
C1-M2-D1	x	x	x	x	x		x		x	x	x		x	
C2-M1-D1	x	x	x	x	x		x		x	x	x		x	
C2-M2-D1	x	x	x	x	x		x		x	x	x		x	
C2-M1-D2		x	x	x	x	x			x	x				
C2-M2-D2		x	x	x	x	x			x	x				
C1-M1-D2	x	x	x		x	x			x					
C1-M2-D2	x	x	x		x	x			x					

Variations in subjective judgments, underlain by different values, can thus lead to different appraisals of infrastructure alternatives.

CONCLUSION. The selection of water-supply projects should be made according to multiple criteria, and drought is apt to influence how well a project meets one or more of those criteria. The evaluation of the projects should thus take into account the likelihood of droughts of different magnitude and duration and the effect they have on overall system goals. Just as important, however, is the evaluation of goal importance, a process which is inherently value-laden and quite likely political. Neither drought-likelihood estimation nor goal appraisal should be regarded as purely technical enterprises. A general approach to project assessment that embodies these characteristics first builds a multiattribute value model (e.g., via the AHP) to determine project priorities and then employs the priorities as weights in the objective function of a mathematical program. The model's output identifies the optimal set of projects to be selected.

Groundwater Management and Land-Use Planning in Central O'ahu

Land and fresh water are two commodities often in short supply on small tropical islands, and this situation is of pivotal concern to residents of O'ahu, the most populous of the Hawaiian islands (Fig. 82). With the island already experiencing a severe housing shortage and its population projected to grow by some 165,000 people over the next 20 years—a 20% increase—planners and public officials have been confronting key decisions regarding how best to accommodate the increase. Reflecting many different considerations, the Oahu General Plan was amended in early 1989 to reduce population ceilings in the Primary Urban Area, stretching from Pearl City to Honolulu, while substantially raising the limits for the 'Ewa Plain and Central O'ahu (Fig. 82). Under this plan, these three areas will absorb about 85% of the expected growth. The new plan will allow a population increase of 41,000 people in the Central O'ahu planning district (Kresnak 1989), markedly greater than the additional 11,500 that could be accommodated under the previous limits. Given a major initiative to develop a new town in 'Ewa, little disagreement exists over the new ceiling in that area. The increased allocation to Central O'ahu, however, is far more controversial.

The decision to open up Central O'ahu to new urban development is a major departure from the strategy set forth in the previous General Plan. In that document, low limits on development were set in order to preserve prime agricultural land and maintain the area's rural character. Despite this policy, Central O'ahu has been the island's greatest growth area during the past 20 years (Kresnak 1989), to the extent that prescribed development capacity was eventually exhausted and a number of proposed developments put on hold as a consequence. The threat to agriculture and open space, the increased traffic and congestion, and the high cost of land and utility development accompanying this growth were seen as reasons for directing further urban development toward the 'Ewa plain. These concerns continue to be voiced by those opposed to the new plan.

Another concern is water. In discussions of the "carrying capacity" of the island, it is often viewed as the most significant determinant. Groundwater is the source for about 92% of O'ahu's water use, with the aquifers of the Pearl Harbor Groundwater Control Area (PHGCA) providing water to Central O'ahu as well as to other districts (Board of Water Supply 1982). Despite a reduction in sugarcane cultivation beginning at the end of the 1970s, and the increasing replacement of furrow irrigation by drip irrigation, rapidly growing municipal demands in tandem with drought conditions throughout most of the 1980s have meant that allocated withdrawal rights for the Pearl Harbor basin are close to, if not already exceed, the aquifers' sustainable yield (Yuen and Associates 1988).

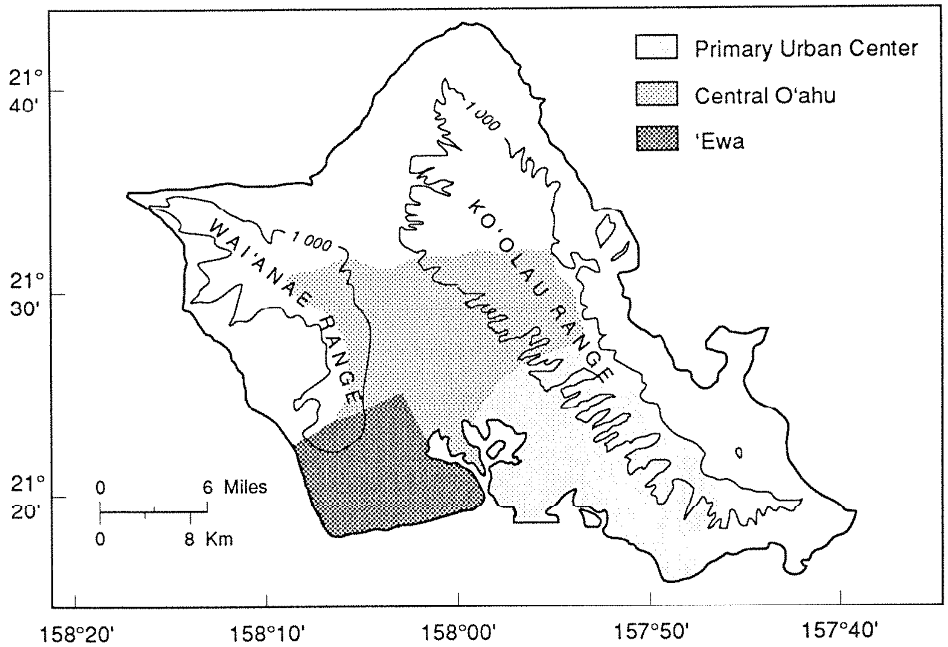


Figure 82. Three of eight planning districts in relation to two major topographic features, Ko'olau and Wai'anae mountain ranges, O'ahu Island

It was within this context that the County Planning Council decided to raise population limits in Central O'ahu. In the end, the pressure to free up land for housing in the end outweighed desires to preserve agricultural land and minimize further demand for groundwater.

To understand the implications of this decision, one needs to know, at the very least, the impacts on groundwater and agricultural land attendant with additional urban development. This is a complex question because the basin-wide water balance, and hence groundwater levels, are affected not only by land use and irrigation regime but also by the specific location of such within the area. This latter factor is critically important since precipitation and evapotranspiration vary greatly within the area. The effects upon groundwater recharge brought about by changes in land use and irrigation technology in one place may be quite different from those of similar changes elsewhere. Any assessment of hydrological impacts must therefore consider explicitly the spatial pattern of land-use changes within the area. Furthermore, since the net effect of different land-use patterns upon groundwater and total agricultural land consumption may be similar, it follows that there may exist a variety of plans all equally attractive *vis à vis* these concerns.

Is water really a constraint to further urbanization of Central O'ahu, and if so, how severe a constraint is it? What spatial pattern(s) of urban growth would be most desirable with respect to groundwater and agricultural land preservation, and how would these patterns vary if reducing water demand during drought were a consideration? This section presents a two-step approach to answering these questions. First, a water-balance model is used to estimate site-specific hydrological effects resulting from changes in land use and irrigation technology. These effects are then integrated with other land-use concerns in a multiobjective programming model that can show the tradeoffs among the concerns mentioned earlier.

REGIONAL HYDROLOGY. Open-ocean rainfall in the vicinity of the Hawaiian Islands is estimated to be approximately 600 mm/yr (Elliott and Reed 1984). Because of the orographic and thermal effects of the land, rainfall ranges from 250 to 11,000 mm/yr for locations on the islands. Steep gradients in rainfall coincide with persistent orographic clouds anchored to topographic barriers. Solar radiation, temperature, and evaporation also exhibit high spatial variability related to topographic relief. On O'ahu, high rainfall and low evaporation along the Ko'olau mountain crest produce substantial water surplus, most of which percolates through the porous soil and rock and recharges underlying aquifers. Leeward of the Ko'olaus, rainfall diminishes rapidly. Resulting natural recharge rates within the Pearl Harbor basin range from more than 4,000 mm/yr along the Ko'olau crest at the northeast corner of the basin to less than 100 mm/yr along the leeward coastline (Giambelluca 1986).

LAND USE IMPACTS ON HYDROLOGY. Agricultural and urban land uses in the basin have large impacts on recharge rates by altering runoff and evaporation characteristics and by the addition of irrigation. Furrow irrigation was the dominant technology in sugarcane cultivation until the late 1970s when most fields in the basin were converted to drip irrigation systems. Under furrow irrigation, the annual applied water typically reached 3 m annually. The conversion to drip irrigation increased the amount of water used by the crop while reducing both the irrigation requirement and the recharge rate. King (1988) found that conversion to drip irrigation increased sugarcane evapotranspiration by 18% on average and reduced recharge by 55%. For the two plantations studied, water applied as irrigation decreased by an average of 32%.

The pineapple crop in Hawai'i has a much lower water requirement than sugarcane. Ekern (1965) showed that pineapple water-use averages about 20% of sugarcane use under optimal conditions. As a result, groundwater recharge is enhanced under pineapple. Until the recent introduction of drip irrigation in some fields, very little irrigation was applied. Drip-irrigated fields now receive about 300 mm/yr.

The most obvious effect of urbanization on the water balance is the increase of surface runoff. Medium-density residential land in Central O'ahu (precipitation = 1,000 mm/yr) was estimated to produce about 2.6 times the runoff of undeveloped land (Giambelluca 1986). High density urbanization produced 4.2 times the undeveloped land runoff. Substantial amounts of irrigation are applied in the form of residential lawn watering and especially golf-course sprinkling. Paved surfaces reduce the evaporative surface area and tend to focus rainfall into smaller areas. The result is that urbanization may either decrease or (in the drier areas of O'ahu) increase groundwater recharge. In Central O'ahu, recharge is greater for urbanized surfaces than undeveloped surfaces, and recharge increases with the level of urbanization (Giambelluca 1986).

Net Groundwater Effects of Land Use Conversions. For the purposes of this study, a portion of the Pearl Harbor basin was selected and subdivided into seven regions (Fig. 83). The study area is one in which agricultural land uses, principally sugarcane and pineapple, are rapidly giving way to urbanization. The regional subdivision for this study was done on the basis of natural landscape divisions in the form of steep-sided stream gulches separating relatively flat land fit for cultivation or urban development. Other boundaries were imposed on the basis of current land use and climate. For these seven regions, the net impacts on groundwater availability of possible land-use conversions were estimated. To do so, estimates of groundwater recharge and water use associated with each land use and each region were needed.

Groundwater recharge was estimated for nine land-use categories and seven regional subdivisions, using a water-balance simulation model. The model is a variant of the Thornthwaite procedure (Thornthwaite and Mather 1955) as modified by Giambelluca (1986). In the model, inputs into the soil-plant system, precipitation and irrigation, are monitored. Runoff is estimated from streamflow data and from values derived using the Soil Conservation Service (1972) runoff curve number method. Evapotranspiration and recharge are determined in the model on the basis of potential evapotranspiration and the model's running estimate of soil-water content. Precipitation is determined using measurements from a dense network of gages. Irrigation for various agricultural and urban land uses is estimated from a variety of information sources, including plantation irrigation records, water-use data, and personal communications. For urban uses, a single rate is used for each land use. For furrow- and drip-irrigated sugarcane, spatial variation in irrigation is recognized. The water-balance simulation is run using a historical, 30-year climate record. Separate runs are made of each region and each land-use type. Simulated groundwater recharge rates are given in Table 42 for each land use and region.

Each of the major land-use types found in central O'ahu has an associated water demand. Based on irrigation estimates and residential and commercial water-use figures, water demand associated with each land use and region was estimated for this study (Table 43). Groundwater-recharge and water-demand values given in Tables 42 and 43 were used to compute net groundwater effects of each land-use conversion.

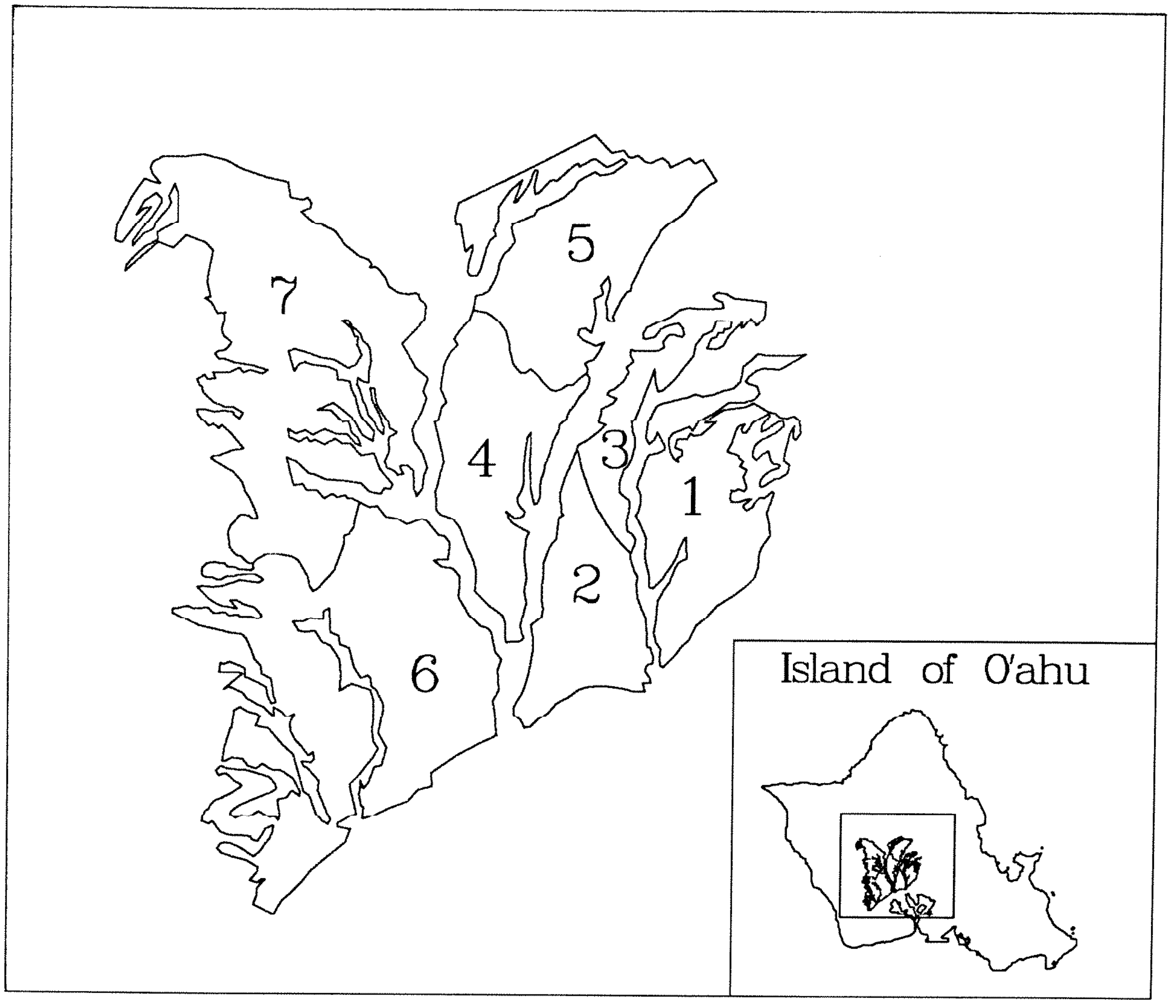


Figure 83. Study area with subregions, O'ahu Island

TABLE 42. GROUNDWATER RECHARGE AS FUNCTION OF LAND USE AND REGION

LAND USE	GROUNDWATER RECHARGE (mm/yr) REGION 1	2	3	4	5	6	7
Residential Low Density	340	227	394	270	437	232	322
Residential Medium Density	460	301	526	362	571	320	443
Commercial and Industrial	561	393	586	444	630	401	500
Parks and Golf Course	353	233	413	278	457	237	333
Sugar (Furrow Irrig.)	1941	1837	2144	2049	2541	2229	2179
Sugar (Drip Irrig.)	1268	1254	1503	1449	1509	1268	1163
Pineapple (No Irrig.)	825	559	873	654	965	586	791
Pineapple (Drip Irrig.)	1126	826	1178	950	1269	860	1086
Vacant/Grazing/Forest	194	153	231	152	268	143	177

TABLE 43. WATER DEMAND AS FUNCTION OF LAND USE AND REGION

LAND USE	WATER DEMAND (mm/yr) REGION 1	2	3	4	5	6	7
Residential Low Density	895	895	895	895	895	895	895
Residential Medium Density	1169	1169	1169	1169	1169	1169	1169
Commercial and Industrial	1027	1027	1027	1027	1027	1027	1027
Parks and Golf Course	317	317	317	317	317	317	317
Sugar (Furrow Irrig.)	2168	2315	2129	2326	2486	2689	2458
Sugar (Drip Irrig.)	1576	1879	1524	1794	1479	1849	1554
Pineapple (No Irrig.)	0	0	0	0	0	0	0
Pineapple (Drip Irrig.)	305	305	305	305	305	305	305
Vacant/Grazing/Forest	0	0	0	0	0	0	0

PROGRAMMING LAND-USE CHANGES. Further urban development in Central O'ahu will not only affect the water balance in the Pearl Harbor Ground Water Control Area (PHGWCA), it will undoubtedly occur at the expense of land currently in agriculture and open space. To design patterns of land-use change that would best achieve goals concerning groundwater management and preservation of agricultural land, an optimization-based approach was adopted. Since much uncertainty surrounds the aquifers' sustainable yield and the amount of land that should be retained for agricultural use, the primary purpose of the modelling effort was to gain a better understanding of the interrelationships among such goals that could then be used to inform planning strategies, rather than to identify an unequivocally best pattern.

Multiobjective Optimization Model. The following vector optimization problem was formulated as the baseline model. Let x_{ijk} be the amount of land ($m^2 \times 10^3$) to change from use i to use j in

TABLE 44. LAND-USE TRANSITIONS CONSIDERED IN PROGRAMMING MODELS

FROM LAND USE (Zone Number)	TO LAND USE								
	SF	SD	PN	PD	PG	VG	RL	RM	CI
SF: Sugar, Furrow Irrig. (2,6)	*	*			*	*	*	*	*
SD: Sugar, Drip Irrig. (2,4,6,7)		*			*	*	*	*	*
PN: Pineapple, No Irrig. (2,3,4,5)				*	*	*	*	*	*
PD: Pineapple, Drip Irrig. (7)				*	*	*	*	*	*
PG: Parks and Golf Courses (1,4,5)					*		*	*	*
VG: Vacant/Grazing/Forest (1,2,3,5,6,7)	*	*	*	*	*	*	*	*	*

NOTE: RL = residential, low density; RM = residential, medium density; CI = commercial-industrial.

zone k. These variables correspond to the transitions indicated in Table 44. Then we wish to find **x**, the vector of values for x_{ijk}, that optimizes $\mathbf{z} = [z_1,z_2,z_3]$, where

$$z_1 = \text{AGCONV [land conversion out of agriculture (ha)]} \tag{B-1}$$

$$z_2 = \text{NETGW [net change in rate of groundwater withdrawal, (gpd} \times 10^3\text{)]} \tag{B-2}$$

$$z_3 = \text{NETDEM [net change in water demand arising from changes in agricultural irrigation, residential use (including lawn watering), and commercial use, (gpd} \times 10^3\text{)]} \tag{B-3}$$

subject to:

1. all land accounted for and supply not exceeded,

   $$\sum_j x_{ijk} = L_{i,k} \qquad \text{for all } i,k \tag{B-4}$$

   where $L_{i,k}$ is the amount of land currently under use i in zone k.
2. compute the net change in recharge with a change in land use,

   $$\sum_{ijk} r_{ijk}x_{ijk} - \text{MORERCHG} + \text{LESSRCHG} = 0 \tag{B-5}$$

   where r_{ijk} is the net change (mm/yr) and MORERCHG and LESSRCHG the net increase and decrease, respectively (m^3/yr).
3. compute net rise (RESWAT) in residential water use (m^3/yr),

   $$\sum_{ik} (w_1x_{i7k} + w_2x_{i8k}) - \text{RESWAT} = 0 \tag{B-6}$$

   where w_1 is the use (m^3/yr) per unit of low-density residential land (use type 7), w_2 the use per unit of medium-density residential land (use type 8);
4. compute net rise (COMWAT) in commercial water use (m^3/yr),

   $$\sum_{ik} cx_{i9k} - \text{COMWAT} = 0 \tag{B-7}$$

   where c is the use (m^3/yr) per unit of new commercial land (use type 9);

5. compute net change in irrigation (m^3/yr),

$$\sum_{ijk} t_{ijk}x_{ijk} - \text{MOREIRR} + \text{LESSIRR} = 0 \qquad \text{(B-9)}$$

where t_{ijk} is the net change (mm/yr) per unit of land change ijk, and MOREIRR and LESSIRR the cumulative net increase and decrease, respectively (m^3/yr).

6. compute total net change in groundwater recharge minus withdrawal, NETGW (gpd × 10^3), converting from m^3/yr to gpd × 10^3,

$$(0.724)\ [\text{MORERCHG} + \text{LESSIRR} - \text{LESSRCHG} - \text{MOREIRR} - \text{COMWAT} - \text{RESWAT}] - 1000\ \text{NETGW} = 0\,; \qquad \text{(B-9)}$$

7. compute total net change in demand, NETDEM (gpd × 10^3),

$$(0.724)\ [\text{MOREIRR} - \text{LESSIRR} + \text{RESWAT} + \text{COMWAT}] - 1000\ \text{NETDEM} = 0\,; \qquad \text{(B-10)}$$

8. calculate AGCONV, land conversion out of agriculture,

$$\sum_{ijk} x_{ijk} - 10\ \text{AGCONV} = 0 \qquad \text{(B-11)}$$

where i is an agricultural use, j is nonagricultural;

9. accommodate additional residential population,

$$\sum_{ik} (p_1 x_{i7k} + p_2 x_{i8k}) = 40{,}000 \qquad \text{(B-12)}$$

where p_1 and p_2 are the average number of people per unit of low-density and medium-density residential land, respectively;

10. calculate COMLAND, the amount (ha) of new commercial and industrial land,

$$\sum_{ijk} x_{ijk} - 10\ \text{COMLAND} = 0$$

where i is noncommercial and j is commercial;

11. calculate LANDRL and LANDRM, the amount (ha) of new low-density and medium-density residential land respectively,

$$\sum_{ik} x_{i7k} - 10\ \text{LANDRL} = 0\,; \qquad \text{(B-14)}$$

$$\sum_{ik} x_{i8k} - 10\ \text{LANDRM} = 0\,; \qquad \text{(B-15)}$$

12. calculate additional commercial and industrial land required to accompany residential development,

$$\text{COMLAND} \geq m_1\ \text{LANDRL} + m_2\ \text{LANDRM} \qquad \text{(B-16)}$$

where m_1 and m_2 represent multiplier effects.

Two factors were important in developing an operational model of Equations (B-1) to (B-16). First, the relative importance of each objective could not be determined *a priori* due to the highly politicized nature of land development on O'ahu and the uncertainty regarding possible future attainment levels of the three objectives. Second, it is doubtful that planners would be very interested in the minimum possible values of agricultural land loss or water demand; rather, they would want to aim for desirable yet unknown targets. With respect to agricultural land, many believe that changing political (e.g., price supports) and economic conditions are rendering sugarcane cultivation, and even that of pineapple, ever more marginal, and that acreage devoted to these activities will decline irrespective of pressure from urbanization. Thus, planners might wish to examine land-use patterns corresponding to different levels of agricultural land conversion. Reduction of water demand from current levels seems to be an ever-present objective that is of special significance during drought, but during periods of normal rainfall, cutting demand beyond that necessary to eliminate waste is often of limited utility to water management. Reducing it to an absolute minimum, therefore, would probably be a high priority only during the drought events themselves—which are random and commonly of short duration—yet such minimization would contribute to the creation of land-use patterns of great persistence. In conjunction with the desire to identify a variety of land-use patterns, these considerations suggested a generating approach, where AGCONV (z_1) and NETDEM (z_3) would be constrained to meet certain minimum values. Thus the baseline model became MODEL I:

$$\max z_2 = \text{NETGW} \tag{I-1}$$

s.t.

$$z_1 : \text{AGCONV} \leq L_1 \tag{I-2}$$

$$z_3 : \text{NETDEM} \leq L_3 \tag{I-3}$$

$$\mathbf{x} \in \mathbf{F} \tag{I-4}$$

where (I-4) simply denotes the feasibility constraint set (B-4)–(B-16).

Although objectives z_2 (NETGW) and z_3 (NETDEM) both pertain to groundwater management, they address quite different aspects of it. NETGW aims to maintain average aquifer levels reasonably high, such that groundwater yields will be able to meet the demands expected under the new population ceiling. Its focus however, on average levels, based on a 30-year climatic record, ignores shorter-term climatic variations that become quite important during times of drought. On O'ahu, aquifer levels usually drop during dry periods as pumpage increases to meet rising agricultural, residential, and commercial demands for water. Since most aquifer recharge takes place at higher elevations in the Ko‘olau mountains, with consequent long lag times before becoming manifest at the lower-elevation wellfields, the effects of reduced recharge on groundwater heads of the reduced recharge during drought events are negligible. Therefore, land-use patterns based on recharge criteria will be largely ineffective for water management during drought, and instead attention should focus on demand reduction. Thus, the purpose of NETDEM (z_3) is to incorporate in the design of land-use plans the short-term concern with water demand.

Model Results. As a first step, a payoff table (Table 45) was developed to give some idea of the range of values each objective could attain. The table indicates that it is possible to accommodate all 40,000 additional residents at the expense of taking only 145.2 ha out of agriculture. In so doing, however, net groundwater recharge minus withdrawal (NETGW) will decrease by 4.9 mgd and (with NETGW at this level) net demand (NETDEM) will rise by 3.1 mgd. On the other hand, it would be possible to increase NETGW by 3.4 mgd but at the expense of 2,345 ha of agricultural land loss. Although such a plan would lead to markedly less water demand (NETDEM), demand could be reduced still further with a near doubling of agricultural land loss and a large rise in net groundwater withdrawal.

Systematically varying the values of L_1 and L_3 over the ranges shown in their respective columns of the payoff table will generate a variety of solutions to MODEL I. When L_1 and L_3 are binding, the solutions will be noninferior ("nondominated," "efficient," or "Pareto optimal"), that is, no other solution will exist that will improve the achievement of any objective without degrading the attainment of at least one of the others Cohon (1978). Before generating and examining solutions which correspond to values for AGCONV, NETGW, and NETDEM within the ranges shown in Table 45, one should be sure that such values are plausible *vis-à-vis* the planning problem.

The entire range of values for NETGW would indeed be conceivable under the scenario described. A recent reappraisal of sustainable yield of the basal (Wai‘anae and Ko‘olau) aquifers of the PHGWCA (Table 46) resulted in a reduction from the 1985 level of 208 mgd to 181 mgd (Yuen and Associates 1988). Using this estimate, sustainable yield is 23 mgd short of withdrawals already authorized, although it exceeds actual use by 17 mgd (Yuen and Associates 1988). Thus, a plan that allowed NETGW to drop to -4.9 mgd would be acceptable under a policy predicated on the assumption that actual draft would remain considerably lower than allocations, while a policy aimed at increasing NETGW to 3.4 mgd would be consistent with the view that actual use will rise to meet current allocations.

Neither for NETDEM nor for AGCONV will plans corresponding to the full range of values from Table 45 be examined. The maximum cut in demand of 28.9 mgd, accounting for 17.6%

TABLE 45. PAYOFF TABLE FOR THREE OBJECTIVE VALUES

OPTIMIZED OBJECTIVE	OBJECTIVE VALUES*		
	AGCONV (ha)	NETGW (mgd)	NETDEM (mgd)
z_1: AGCONV	145.2	-4.9	3.1
z_2: NETGW	2,345	3.4	-25.3
z_3: NETDEM	4,214	-4.8	-28.9

*AGCONV = land conversion out of agriculture, NETGW = net groundwater, NETDEM = net demand.

TABLE 46. GROUNDWATER ALLOCATION, USE, AND SUSTAINABLE YIELD IN BASAL AQUIFERS OF PEARL HARBOR GROUNDWATER CONTROL AREA, O'AHU

	Koolau Aquifer (mgd)	Waianae Aquifer (mgd)	Total (mgd)
Authorized Total Draft	184	20	204
Sustainable Yield	164	17	181
Current Draft (1983–1986)	149	15	164
Sustainable-Authorized	-20	-3	-23
Sustainable-Current Use	15	2	17

SOURCE: Yuen and Associates (1988).

of current draft, would more than offset the 23 mgd shortfall between authorized withdrawals and the sustainable yield of the basal aquifer. Moreover, consumption can be cut during drought through a variety of short-term means, from voluntary conservation to price hikes to rationing. It is therefore unlikely that land-use planning would be seriously considered as a way to eliminate the entire water deficit that could conceivably occur if existing authorizations were exercised. With respect to AGCONV, the strong likelihood of a reduction in agricultural acreage during the coming decade suggested the use of different land-loss scenarios.

With these assumptions, AGCONV was constrained to values (in ha) corresponding to 11, 15, 20, and 25% of the total amount of land currently in agriculture in the study area, namely,

$$z_1 : \text{AGCONV} \leq L_1 \qquad L_1 \in \{600, 787, 1050, 1312\} . \tag{I-2a}$$

Due to the unpredictable behavior of NETDEM under these constraints, it was allowed to float freely in order to identify a feasible (though dominated) solution for each scenario, whereupon it was varied parametrically to determine tradeoff rates between NETGW and it. Figure 84 shows these tradeoffs along the noninferior frontier under each of the four AGCONV scenarios.

To illustrate the land-use implications of the tradeoffs, optimal land-use changes corresponding to two nondominated solutions under each scenario were determined. Objective attainments for each solution are given in Table 47. The allocation of new residential population was identical in all eight cases (Fig. 85), as were such other important attributes as the proportion of residential land to be developed at medium density (100%) versus low density (0%), and the amount of additional land converted to parks and golf courses (127 ha). Regardless of the scenario or of the achievement of NETGW (z_3) relative to NETGW (z_1), over 75% of the additional residential development should occur in zones 1 and 2, with none located in zones 4, 6, and 7.

The marked differences in objective attainment among the different solutions result from changes between nonresidential land uses. As portrayed in Figure 86, these transitions are confined to changes from sugarcane cultivation to vacant, grazing, or forest uses, all of which would occur in zones 2 and 6.

Several other patterns are also apparent. Solutions which emphasize net groundwater levels over reduction in water demand will tend to have greater proportions of sugarcane land convert to vacant/grazing/forest in zone 6 as the amount of allowable agricultural land loss rises. This is most pronounced where sugarcane is drip-irrigated. No variance in such land-use change will occur in zone 2. Favoring NETDEM over NETGW, however, yields quite different results. In this case, irrespective of how much agricultural land is lost, all furrow-irrigated sugarcane in zone 6 should remain in (nongolf course) open space (vacant/grazing/forest), whereas with emphasis on NETGW all but a fraction of a percent should remain in sugar. In addition, as

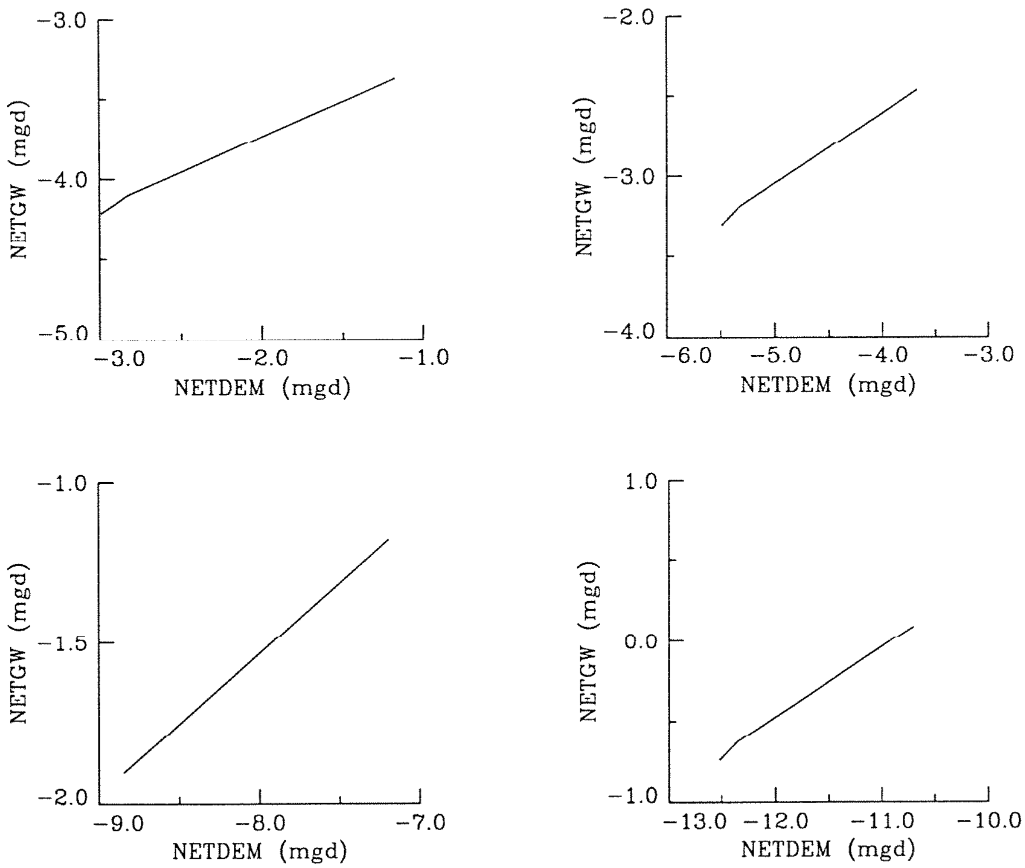


Figure 84. Parametric analysis of NETDEM (net demand) and NETGW (net groundwater recharge minus withdrawal), O'ahu Island

TABLE 47. OBJECTIVE FUNCTION ATTAINMENT FOR SELECTED LEVELS OF AGRICULTURAL LAND LOSS

	AGCONV (ha)	NETGW (mgd)	NETDEM (mgd)
Scenario 1a	600	-3.37	-1.17
Scenario 1b	600	-4.21	-2.99
Scenario 2a	787	-2.46	-3.6
Scenario 2b	787	-3.30	-5.49
Scenario 3a	1050	-1.18	-7.19
Scenario 3b	1050	-1.90	-8.85
Scenario 4a	1312	+0.09	-10.70
Scenario 4b	1312	-0.74	-12.52

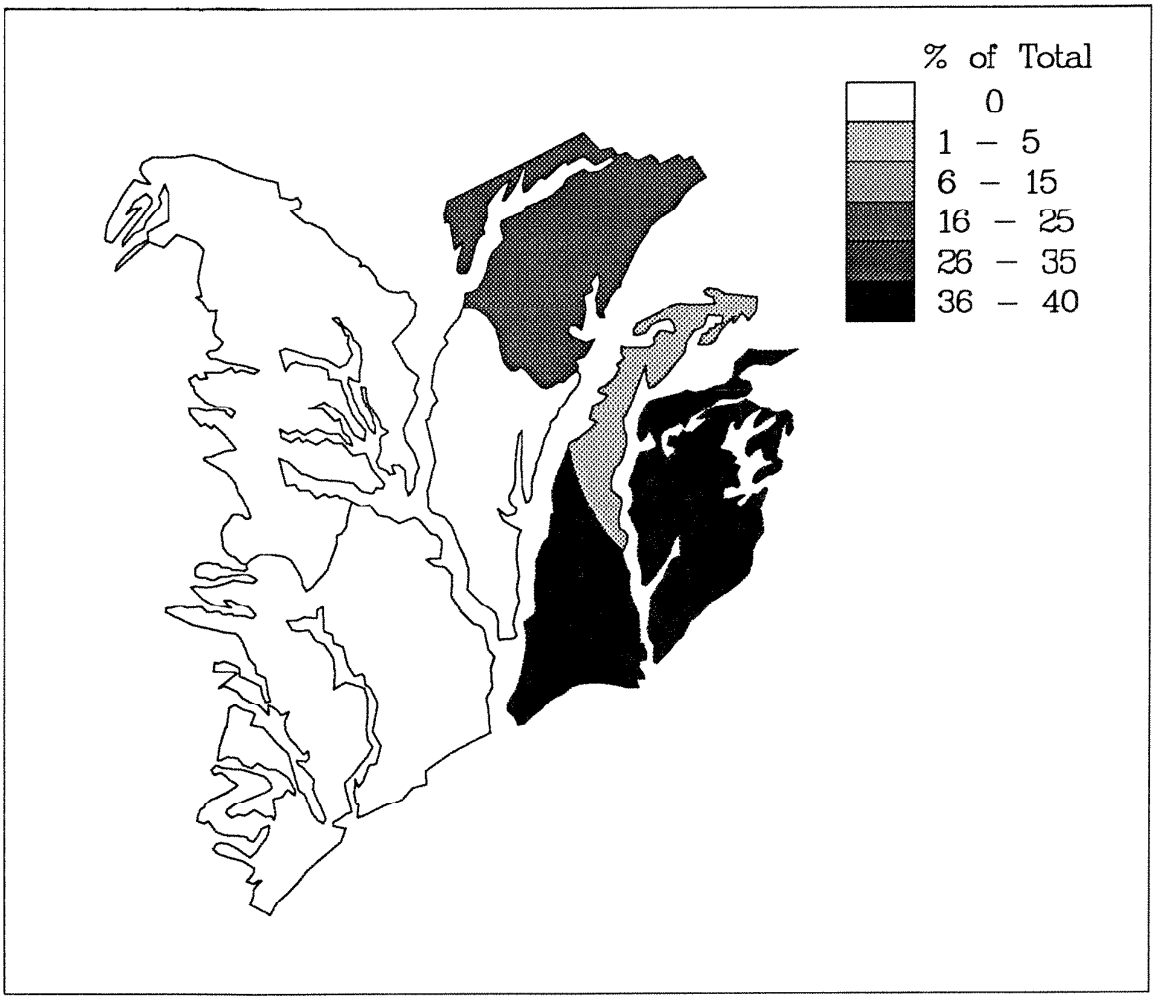
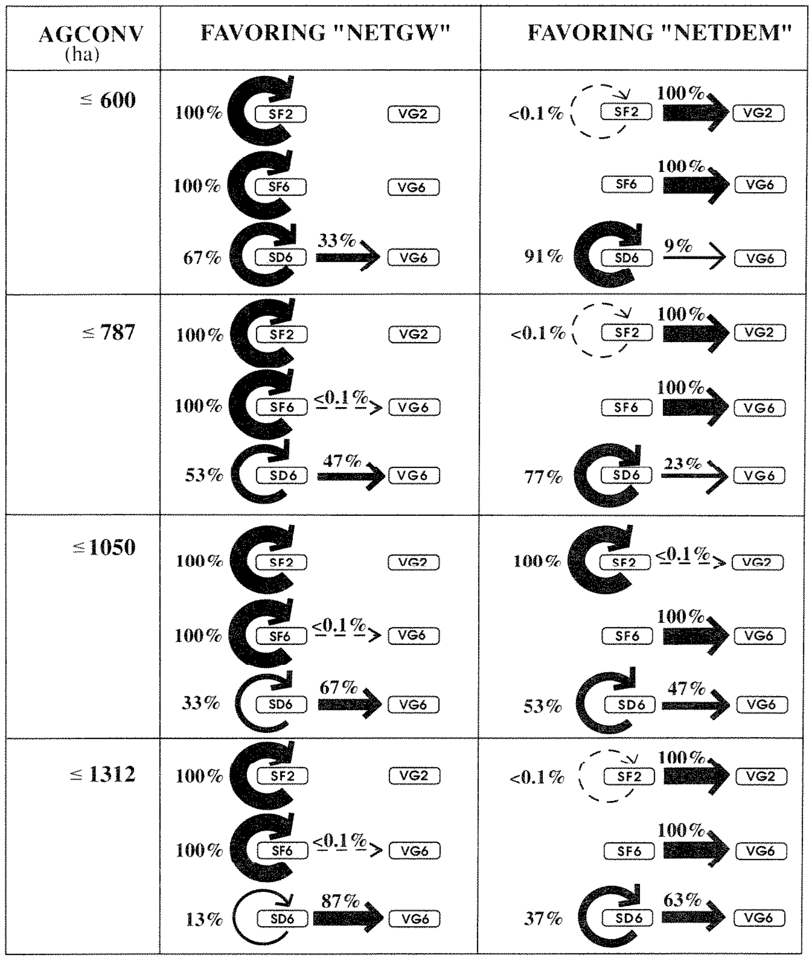


Figure 85. Optimal distribution of 40,000 new residents in Central O'ahu study area



SF2: furrow-irrigated sugar in zone 2.
SF6: furrow-irrigated sugar in zone 6.
SD6: drip-irrigated sugar in zone 6.
VG2: vacant/grazing/forest in zone 2.
VG6: vacant/grazing/forest in zone 6.

Figure 86. Difference in land-use transitions between policy favoring net groundwater recharge (NETGW) vs. one favoring reduction in water demand (NETDEM) with variations in agricultural land conversion (AGCONV)

constraints on agricultural land loss are loosened, the shift out of drip-irrigated sugarcane progresses at a somewhat slower rate than under a policy emphasizing net groundwater recharge.

Most important from the viewpoint of water management are the qualitative differences in optimal land-use changes resulting from different priorities given net groundwater recharge relative to demand reduction. At all levels of agricultural land loss, for almost every type of land-use transition depicted in Figure 86, changes in effective weights yield markedly different changes in land use.

CONCLUSION. Southern O'ahu and the areas fringing Honolulu have seen rapid urban growth throughout the past three decades. Occurring simultaneously with this growth have been a reduction in the areas planted in sugarcane and pineapple and changes in type and extent of irrigation. Paralleling these developments have been changes in the use and replenishment of groundwater in the Pearl Harbor basin, although the precise relationship between the basin's water balance and changes in land-use and irrigation patterns is not a simple one. With pumpage rights possibly already exceeding the aquifers' sustainable yield, and demand for urban land seeming to grow inexorably, there is great concern that water supply and the desire to preserve agricultural land and open space may place tight limits on the amount of urban growth that central O'ahu can sustain.

These limits have been explored by employing the results of a water-balance simulation within a multiobjective land-use programming model. The model identifies optimal land-use changes in seven different subzones of central O'ahu, if planners wished to accommodate 40,000 additional residents while ensuring that agricultural land loss, net groundwater withdrawal resulting from human demands in tandem with recharge dynamics, and water consumption are maintained within prescribed bounds. Particular attention is given to the land-use implications of the tradeoff between maximizing long-term groundwater levels and minimizing water consumption. Among other things, this model assumes that land presently not in agriculture will not be cultivated in the future.

In general, as greater amounts of land move out of agriculture, both water demand and the ratio of groundwater recharge to withdrawal would diminish. In fact, if a quarter of present agricultural land shifted out of sugarcane cultivation and were kept in grazing, forest, or other (nongolf course) open space, the model suggests it would be possible to maintain groundwater recharge-to-withdrawal ratio at current levels. The magnitude of the difference between recharge and withdrawal depends on the change in water demand, but for the cases and ranges examined the difference remains small, varying between 0.73 mgd and 0.84 mgd. Although such differences in goal attainment would likely be of little concern in themselves, the actual land-use conversions required to effect them would be qualitatively different and thus of great import. In this regard, the importance of being able to trim water consumption during drought periods through more effective land-use arrangements, as compared to maintaining average groundwater heads at current levels, needs to be articulated.

Different spatial patterns of land use and land cover, especially in areas characterized by steep rainfall and evaporation gradients, can have profound effects on groundwater recharge, irrigation, and residential outdoor water use. Planners should determine the degree to which land-use patterns could help achieve water-management objectives related to such elements and should evaluate the merits and drawbacks of plans designed to effect such patterns. Any given pattern may well affect the achievement of different water-management goals in quite different ways, forcing planners and managers to articulate desirable tradeoffs. Water-resource management that treats water separately from land use is doomed to be ineffective, inefficient, or both. It needn't be that way.

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APPENDIX CONTENTS

Appendix Figures

Table

APPENDIX A. BMDI AND DAI CALCULATIONS

The following is a summary of the procedures used to calculate BMDI and DAI, slightly modified after Bhalme and Mooley (1980).

MOISTURE INDEX. Utilizing the percentage departure of monthly rainfall from the long-term mean and the reciprocal of the coefficient of variation, a moisture index (M_k) for each month is calculated as,

$$M_k = \frac{100(x_k - X_m)}{\sigma_m} \tag{A.1}$$

where x_k is the monthly rainfall, X_m is the long-term monthly mean, and σ_m is the long-term monthly standard deviation. A cumulative moisture index ($CM_{t,k}$) is calculated as,

$$CM_{t,k} = \sum_{n=k-t+1}^{k} M_n \tag{A.2}$$

where k is the month and t is the duration (months).

DROUGHT INTENSITY INDEX. To develop a drought intensity index, the minimum (greatest negative) cumulative moisture index for 1-, 2-, 3-, and 4-mo durations ($CM_{t,min}$) are found at each station,

$$CM_{t,min} = \min[CM_{t,k}] \quad \text{for } t = 1, 2, 3, 4\,. \tag{A.3}$$

Regional averages of the minimum at each duration (for our study, the average of all network stations on each island) are used to obtain a least-squares fit for the line,

$$CM_{t,min} = a + bt\,. \tag{A.4}$$

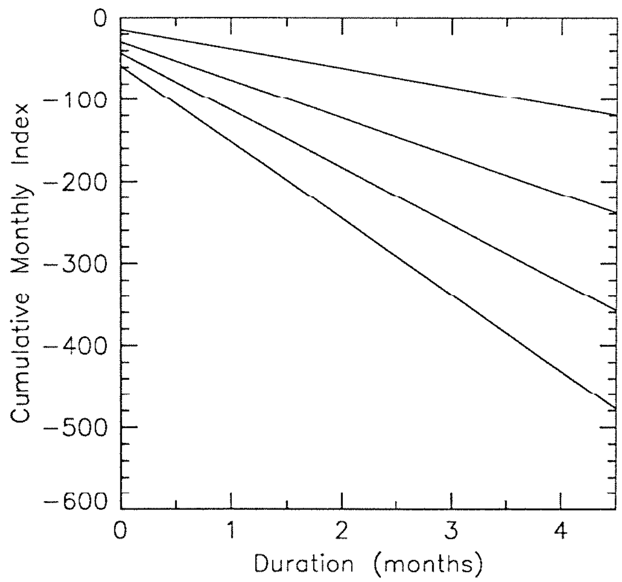
This is the lowermost line in Appendix Figure A.1. Following Palmer (1965), Bhalme and Mooley divide the area between zero and the line into four equal parts shown by the dashed lines, label them as boundaries between extreme, severe, moderate and mild drought, and give the respective numerical values -4, -3, -2 and -1.

A preliminary drought intensity index can be obtained by scaling the moisture index according to the lines shown in Appendix Figure A.1. The equation for such an index is gotten by setting $I_k = -4$ for $CM_{t,k} = CM_{t,min}$ to get,

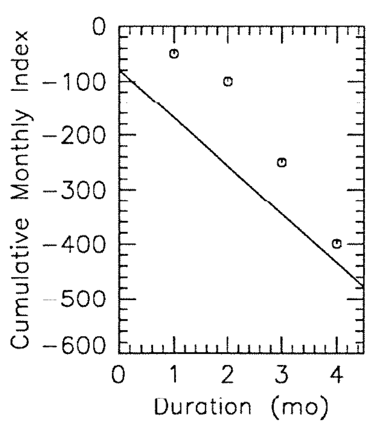
$$I_k = \frac{CM_{t;k}}{[-0.25(a + bt)]} \tag{A.5}$$

where I_k is the drought intensity index for the kth month, a and b are the constants determined for Equation (A.4).

In applying this procedure it was found that unrealistic values are produced in some situations. For example, assume that two months with $M_k = -50$ followed by two months with



Appendix Figure A.1. Accumulated monthly index vs. duration



Appendix Figure A.2. Accumulated monthly index vs. duration for 2 mo with M = -50, followed by 2 mo with M = -150

M_k = -150 as shown in Appendix Figure A.2. Now if instead we assume that the first two months were wet, the dry period begins when the moisture index falls below zero as shown in Appendix Figure A.3. Notice that in the first case the points all lie above the extreme drought line even though all months had below mean rainfall, while in the second an extreme drought condition exists after only two months of below mean rainfall following two months of normal or above normal rainfall. This points to the need to take into consideration the antecedent conditions.

To include the effects of antecedent conditions, the contribution of each month to the severity of the drought is first determined by setting t = 1 in Equation (A.5) as

$$I_k = \frac{CM_k}{[-0.25(a + b)]} \,. \tag{A.6}$$

Since for the previous month t = 0, $I_{k-1} = 0$ so that the change in I_k is,

$$\Delta I_k = I_k - I_{k-1} = \frac{M_k}{[-0.25(a + b)]} \,. \tag{A.7}$$

In successive months a negative value of the moisture index, M_k, will be necessary for the drought to maintain a given severity, but one month with normal rainfall in the middle of many months of below normal rainfall should not be allowed to end a drought. The rate at which M_k must decrease will depend on the value of I_k which is to be maintained. This can be done by adding a term to carry-over antecedent conditions:

$$\Delta I_k = \left\{\frac{M_k}{[-0.25(a + b)]}\right\} + cI_{k-1} \tag{A.8}$$

where c is a constant. The value of c is determined such that the severity of an existing dry period is maintained if I_k remains constant. From Equation (A.5) the value of M_k may be calculated for two consecutive months for some constant value of I_k. This value of M_k may then be substituted into Equation (A.8) to determine the value of c. For example, assume the value of I_k is -1 for two consecutive months, the second and third months of a dry period. Then from Equation (A.5),

$$-1 = \frac{CM_{2;k-1}}{[-0.25(a + 2b)]} \tag{A.9}$$

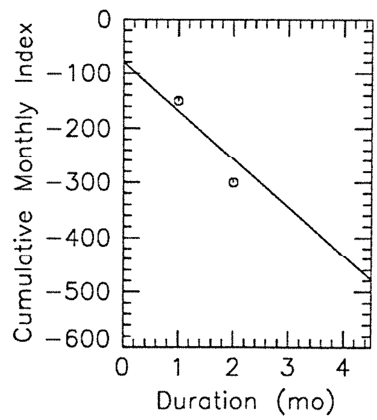
and

$$-1 = \frac{CM_{3;k-1}}{[-0.25(a + 3b)]} \,. \tag{A.10}$$

The value of M_k necessary to maintain the intensity of the dry period is

$$M_k = CM_{3,k} - CM_{2,k-1} = 0.25b \,. \tag{A.11}$$

By substituting this value into Equation (A.8),



Appendix Figure A.3. Accumulated monthly index vs. duration for 2 wet mo followed by 2 mo with M = -150

$$\Delta I_k = \left\{\frac{0.25b}{[-0.25(a + b)]}\right\} - c(-1) = 0 \tag{A.12}$$

and solving for c,

$$c = \frac{-b}{(a + b)} . \tag{A.13}$$

the complete equation for the value of I_k now becomes

$$I_k = I_{k-1} + \Delta I_k = I_{k-1} + \frac{M_k}{[-0.25(a + b)]} + cI_{k-1} \tag{A.14}$$

or

$$I_k = \frac{M_k}{[-0.25(a + b)]} + I_{k-1}\left[\frac{1 - b}{(a + b)}\right] . \tag{A.15}$$

DROUGHT AREA INDEX. Bhalme and Mooley defined a drought area index (DAI) for the year as the percentage of the area of their study (India) with a mean intensity index of -2.00 or less for the four monsoon months, June through September. Because Hawai'i lacks well-defined seasons, a DAI was calculated for each month of the year based on the percentage of the island area with a drought intensity index of -2.00 or less. In this study a drought was defined as any period where the DAI was greater than or equal to 50%, allowing a maximum of 1 consecutive months where the DAI fell below that level. The magnitude of a drought was defined as the mean value of I for all stations and months in the period and the severity was defined as the duration (in months) times the magnitude. The droughts were then ranked according to severity by island as well as state-wide for use in further analysis.

APPENDIX B. ERROR MODELS AND ESTIMATED EQUATIONS FOR TIME SERIES ANALYSIS OF HONOLULU WATER CONSUMPTION, PRICE, AND RAINFALL

Each BWS district has been modeled separately, with autoregressive, seasonal and moving average terms as well as the substantive variables. In the following statement of error models and equations, ϕ represents the autoregressive term; Φ the seasonal autoregressive term; θ the moving average term, ω the transfer function coefficient for each substantive variable, q = pumpage; R = rainfall; P = price; and D = dummy variable for periods of water use restrictions. The backward shift operation B is interpreted as, for example, $B^2x_t = x_{t-2}$, and $(1-B)^2$ indicates a second difference:

$$(1 - B)^2x_t = (1 - 2B + B^2)x_t = x_t - 2x_{t-1} + x_{t-2} = (x_t - x_{t-1}) - (x_{t-1} - x_{t-2}) .$$

For each district, the error model is given first, followed by the estimated transfer function.

Honolulu District:

$$(1 - \phi B^{12}) (1 - \Phi B^{12})u_t = (1 - \theta B)e_t \tag{B.1}$$

$$(1 - B)^2q_t = \alpha + \omega_1(1 - B)^2R_t + \omega_2 (1 - B)^2P_t + \omega_4 D_t + u_t \tag{B.2}$$

Pearl Harbor District:

$$(1 - \phi B - \phi B^{12}) (1 - \Phi B^{12})u_t = (1 - \theta B) e_t \tag{B.3}$$

$$(1 - B)^2q_t = \alpha + \omega_1(1 - B)^2R_t + \omega_3(1 - B)^2P_t + \omega_4 D_t + u_t \tag{B.4}$$

Ewa-Waianae District:

$$(1 - \phi B - \phi B^{11}) (1 - \Phi B^{12})u_t = (1 - \theta B)e \tag{B.5}$$

$$q_t = \alpha + \omega_1 R_t + \omega_3 P_t + \omega_4 D_t + u_t \tag{B.6}$$

Waialua-Kahuku District:

$$(1 - \phi B^{12}) (1 - \Phi B^{12})u_t = (1 - \theta B)e_t \tag{B.7}$$

$$(1 - B)^2 \ln q_t = \alpha + (\omega_1 + \omega_2 B) (1 - B)^2 \ln R_t + \omega_3 (1 - B)^2 \ln P_t + u_t \tag{B.8}$$

Windward District:

$$(1 - \phi_1 B - \phi_2 B^{11})u_t = (1 - \theta_1 B - \theta_2 B^{11} + \theta_3 B^{12})e_t \tag{B.9}$$

$$q_t = \alpha + \omega_1 R_t + \omega_3 P_t + u_t . \tag{B.10}$$

APPENDIX C. THE ANALYTIC HIERARCHY PROCESS*

The AHP is "a theory of measurement" (Saaty 1990, p. 259) that has been developed into a general methodology used to set priorities and aid decisions involving choice and allocation (Saaty 1980, 1982). Following the AHP, one structures a decision problem into a hierarchy the different layers of which correspond, from apex to base, to the primary goal, evaluative criteria and subcriteria, and alternatives. In addition to their usual meaning of "attributes," "criteria" may also refer to constraints, scenarios, inherent properties of the alternatives, or decision makers and other stakeholders. Through pairwise comparison of elements at one level with respect to an element at the level above, the relative priority (weight or dominance) of each element in the hierarchy can be determined. Comparisons are usually (though not obligatorily: see Harker and Vargas 1987, 1990) made using a nine-point intensity scale and priorities determined by solving the eigenvalue problem corresponding to the positive reciprocal matrix containing the comparisons. The priorities derived from each matrix are expressed in units of relative dominance and define a (derived) ratio scale (Saaty 1977, 1990). Multiplication of these individual ("local") priorities up through the hierarchy leads to the alternatives' overall priorities. These will also belong to a ratio scale and thus may be quite useful in resource-allocation decisions.

At the heart of the AHP is the eigenvalue procedure for determining the relative dominance of one element (e.g., alternative, criterion) over another when the elements' absolute weights are unknown (Saaty 1977, 1980). Dominance is determined by a set of comparisons of the elements taken pairwise. The set of pairwise comparisons of a_i with a_j, denoted a_{ij}, where i,j = 1,2,...,n, may be arranged to form a matrix, which we call **A**. To develop the essential concept, let us suppose, for the moment, that the elements' true weights are known—for example, that they are physical items that may be weighed on a balance. If we let w_i be the weight associated with element a_i and w_j the weight of a_j, the comparisons a_{ij} may be represented by the ratio of these known weights; the entries in **A** are thus w_i/w_j. Since **A** is positive and reciprocal, $w_{ji} = 1/w_{ij}$ and the principal diagonal consists of all 1's. Even though the weights are already known, it is instructive to note that they can also be found by solving the linear system

$$\mathbf{A}\mathbf{w} = n\mathbf{w} \tag{C.1}$$

where **w**, the vector of w_i, is the right eigenvector of **A** and n its eigenvalue (Saaty 1980). Here, each w_i can be determined easily from its corresponding row (row i) in **A**. This is

*This brief discussion of the AHP is taken, with only slight modification, from Ridgley and Chai (1990).

because the columns of **A** are linearly dependent on each other, i.e. that **A** has rank 1; the known weights resulted in perfect consistency (cardinal transitivity) among the comparisons.

The usual case is that the true weights are not known, and hence the comparisons will be estimates based on the evaluator's judgment. Imbued with errors of estimation, these comparisons will lack the perfect consistency of trivial cases with known weights. Consequently, the evaluator cannot ascertain the true weights, but rather only an estimate of them. Saaty (1977) has shown that such an estimate may be determined by solving

$$\mathbf{A}'\mathbf{w}' = k_{max}\mathbf{w}' \qquad \text{(C.2)}$$

where $\mathbf{A}'$ is the comparison matrix developed from the evaluator's judgments, $\mathbf{w}'$ is the vector of estimated weights (and the right eigenvector of $\mathbf{A}'$), and k_{max} is the largest eigenvalue of $\mathbf{A}'$. How good one's estimates are of w_i depend on the consistency of the comparisons a_{ij}; that is, it depends on the degree to which ratio transitivity is violated. The consistency index CI

$$CI = \frac{(k_{max} - n)}{(n - 1)} \qquad \text{(C.3)}$$

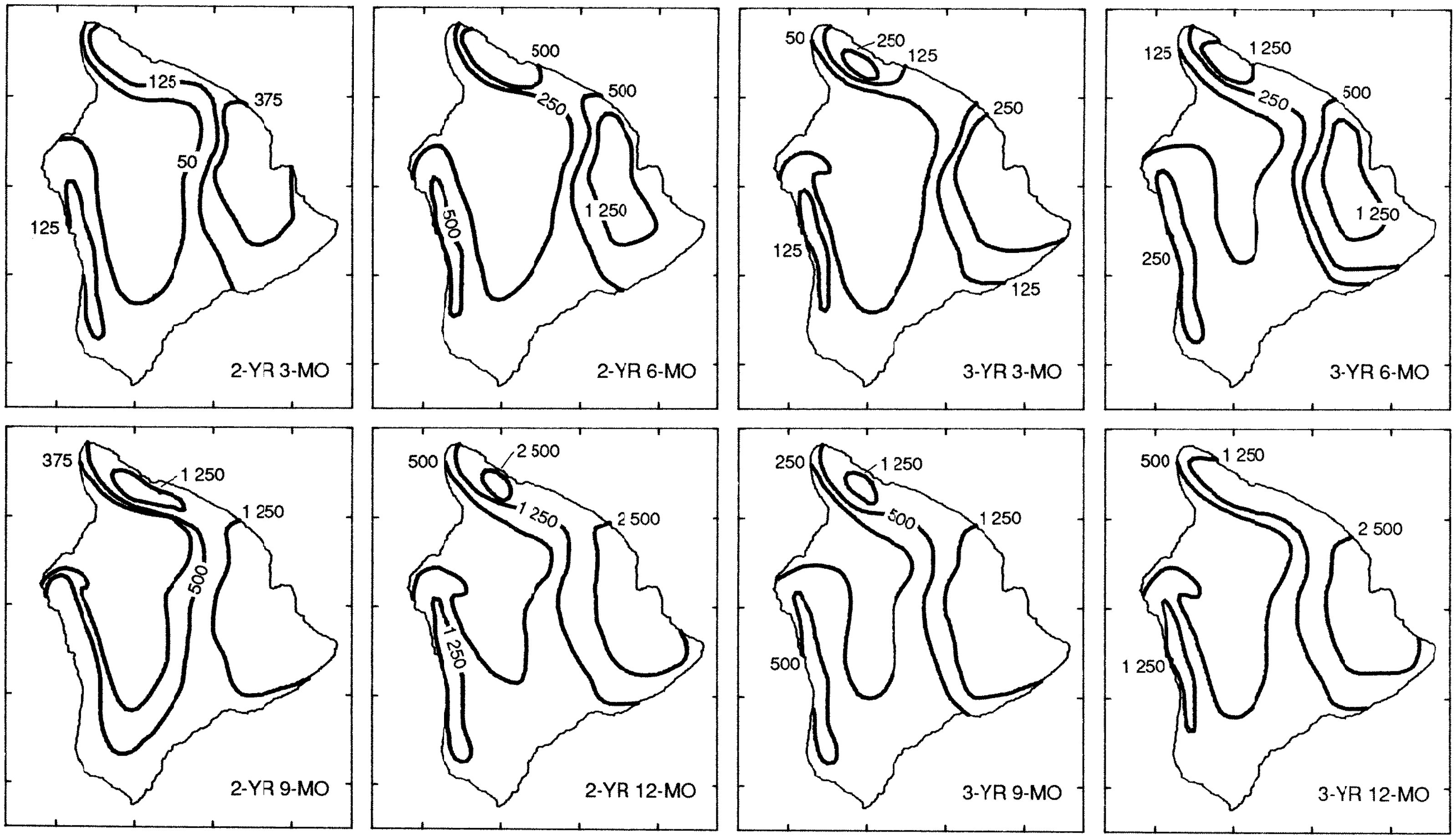
has been developed to show how consistent the comparisons are. When expressed as a percentage of the average CI of randomly generated matrices, it is known as the consistency ratio CR. Consistency is considered adequate when CR is 0.1 or less (Zahedi 1986; Saaty 1980).

The nine-point scale of intensity used in the AHP permits comparisons to be made both numerically and verbally (App. Table C.1). The procedure thus allows assessments of an element's relative dominance which are rather qualitative in character, an attractive attribute in cases where evaluators are uncomfortable with quantitative comparisons. Notwithstanding the "fuzziness" of the scale, comparisons using it have been shown empirically to be highly accurate (Decision Support Software 1986; Saaty 1978; Saaty 1982). Further details on mathematical and computational properties of the eigenvector method and the rationale for the nine-point scale can be found in Saaty (1977, 1978, 1980).

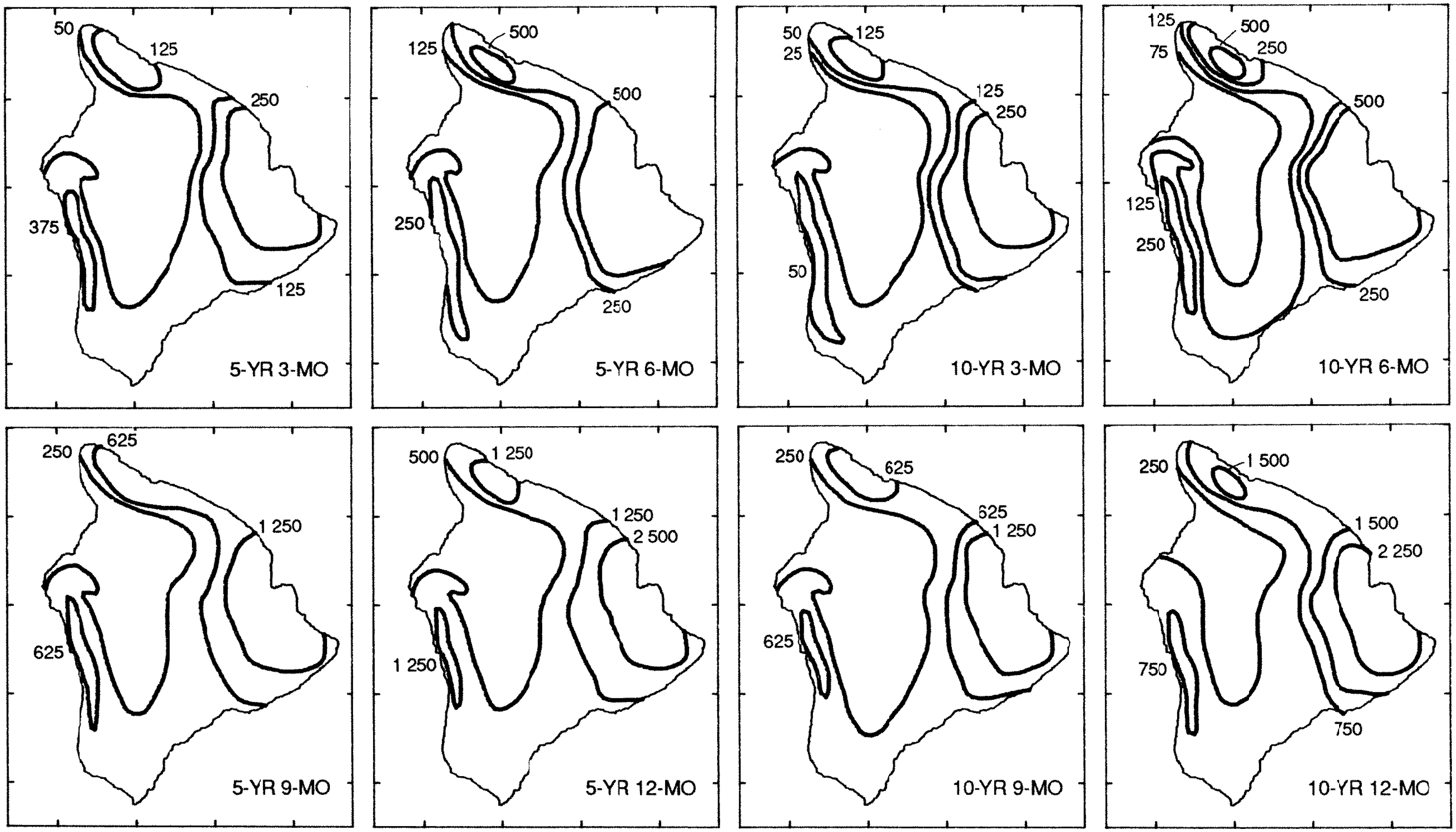
APPPENDIX TABLE C.1. INTENSITY-OF-IMPORTANCE SCALE USED IN ANALYTIC HIERARCHY PROCESS

Intensity of Importance	Definition	Explanation
1	Equal importance	Two criteria contribute equally to the objective
3	Weak importance of one over another	Experience and judgment slightly favor one criterion over another
5	Essential or strong importance	Experience and judgment strongly favor one criterion over another
7	Demonstrated importance in proctive	A criterion is strongly favored and its dominance is demonstrated
9	Absolute importance	The evidence favoring one criterion over another is on the highest possible order of affirmation
2, 4, 6, 8	Intermediate values	When compromise is needed

*SOURCE: After Saaty 1977.



Appendix Figure D.1. Minimum rainfall for 3-, 6-, 9-, and 12-mo durations and 2-, 3-, 5-, 10-, 20-, 30-, 50-, 100-, and 200-yr return periods, Hawai'i Island



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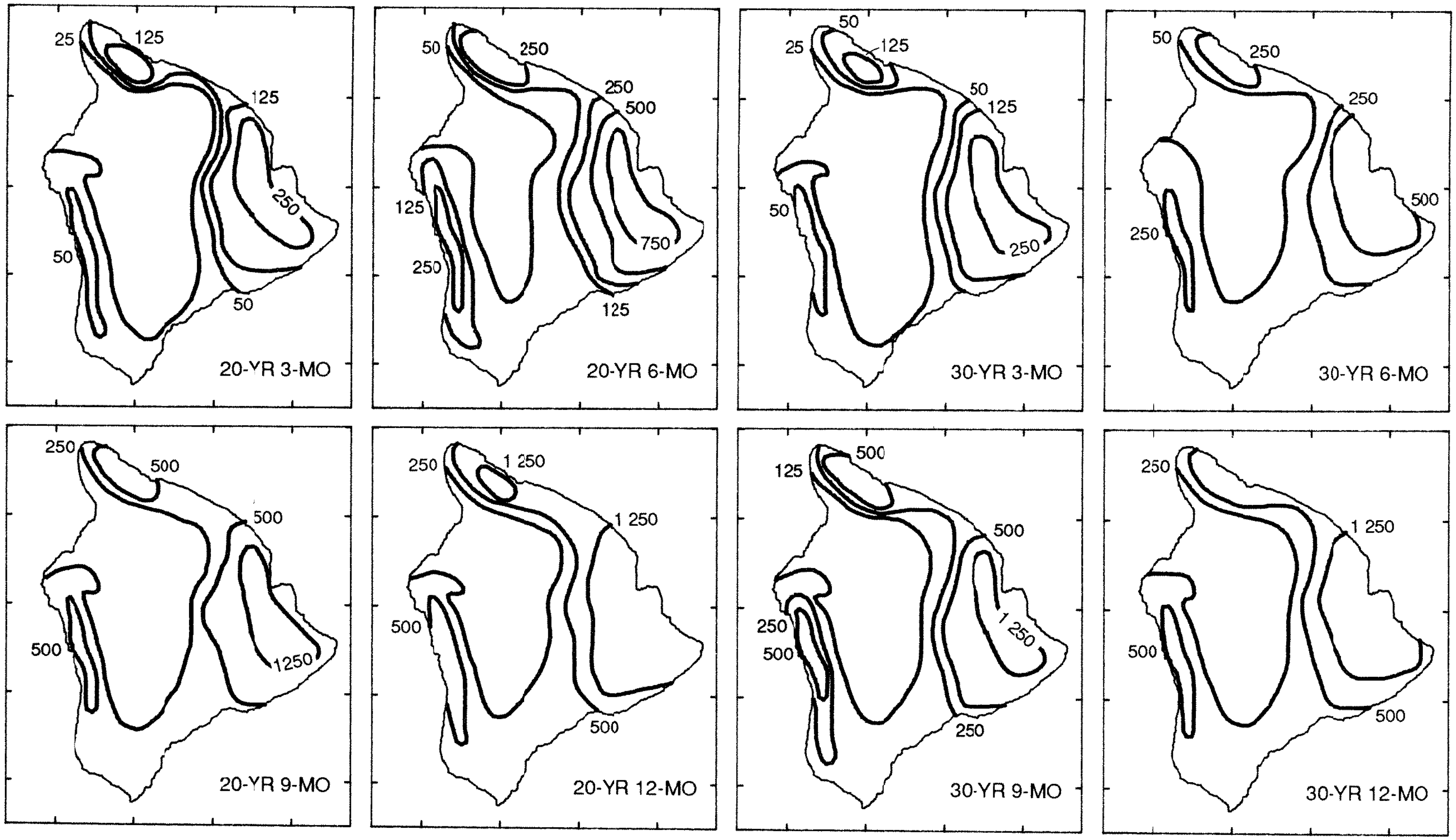

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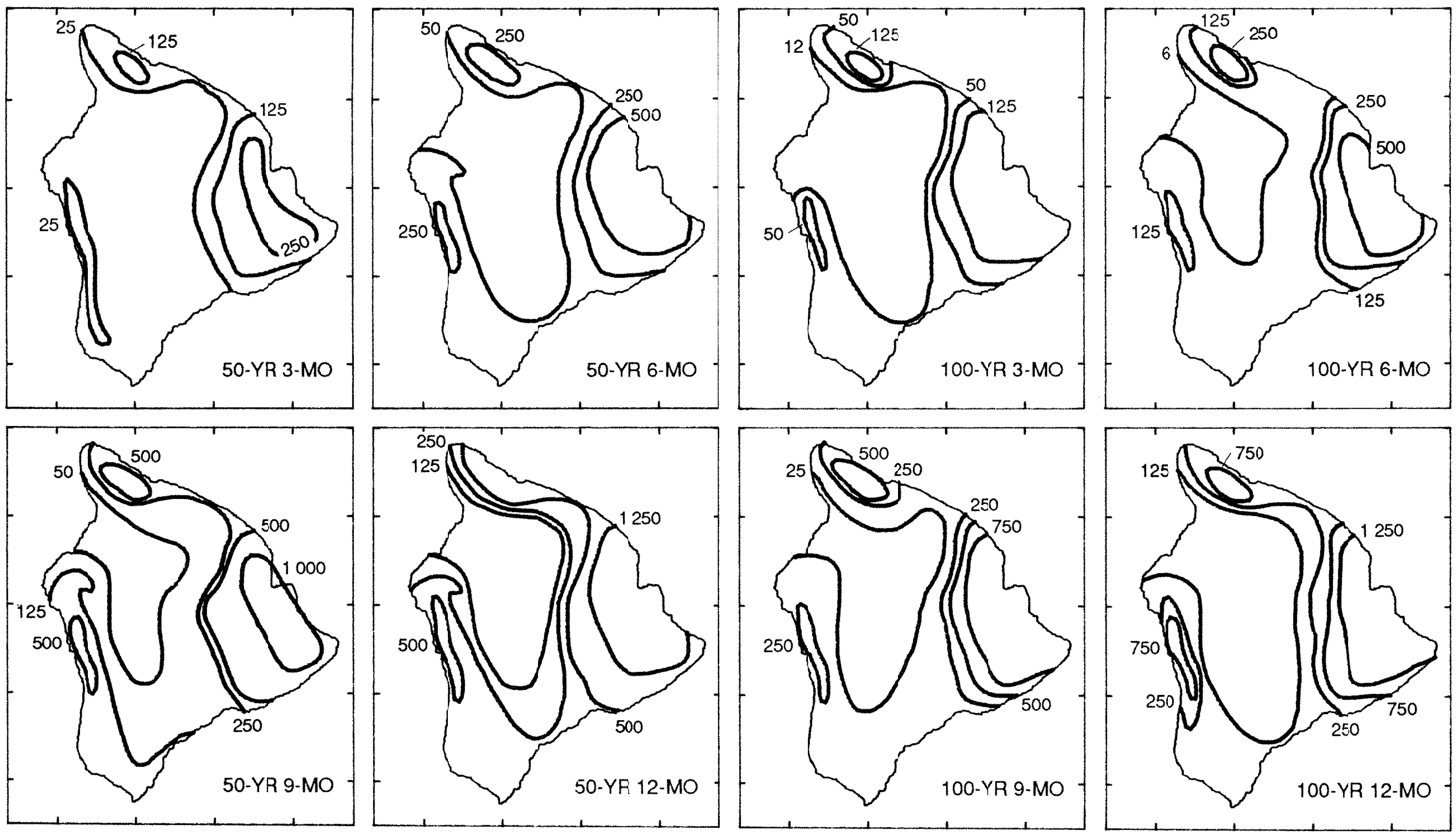

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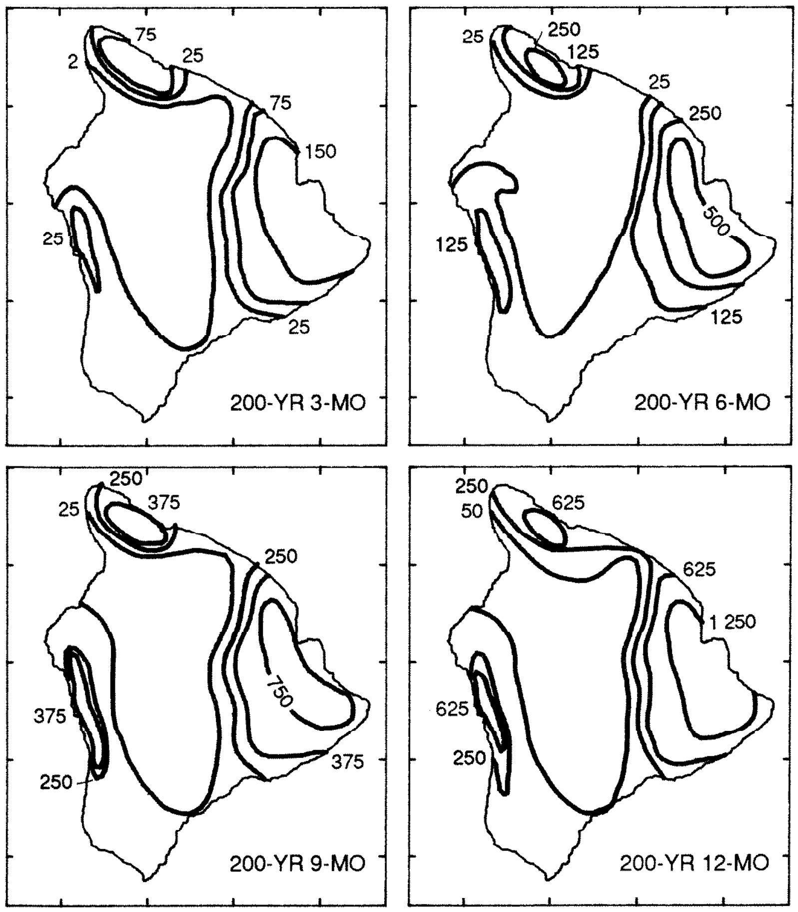
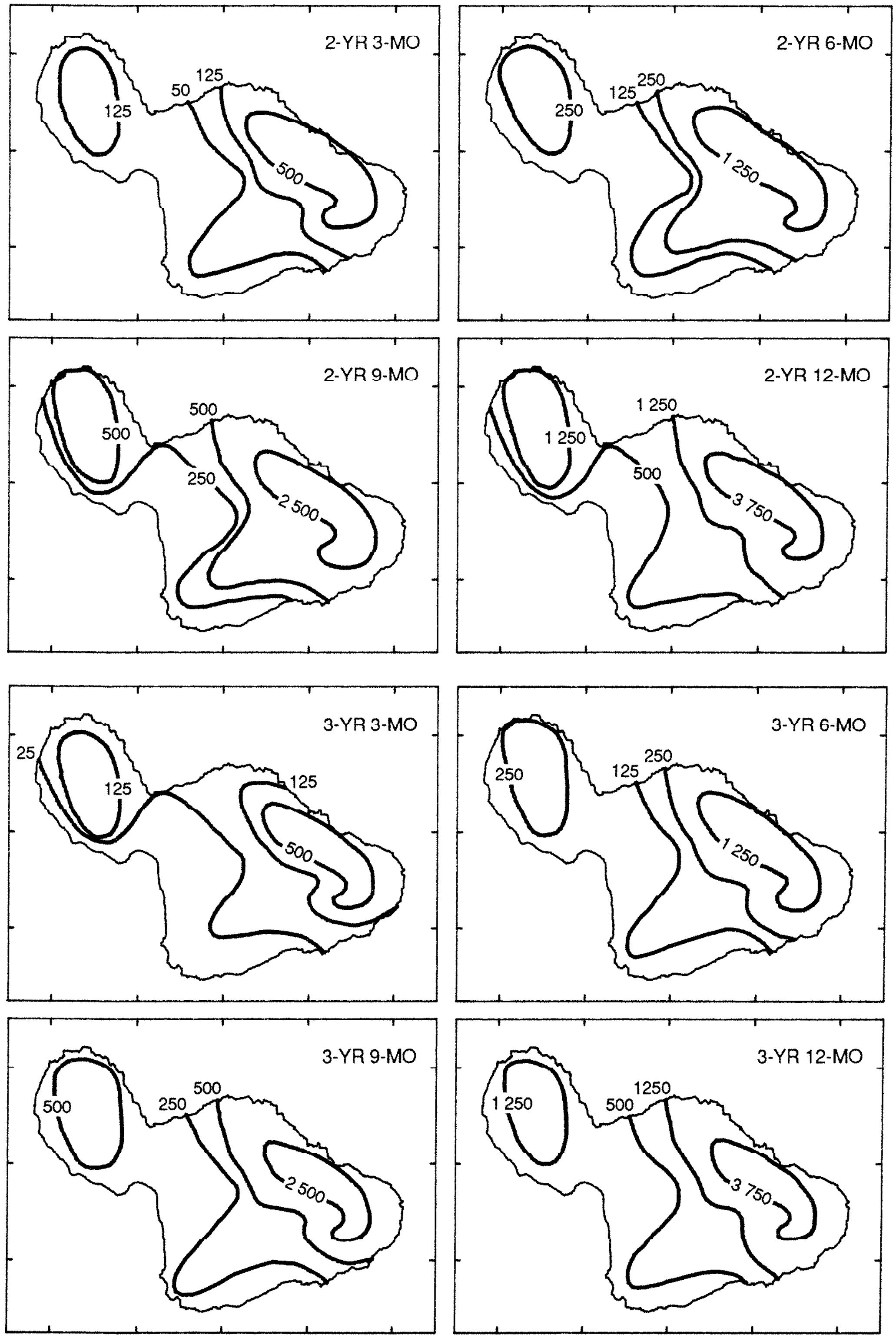
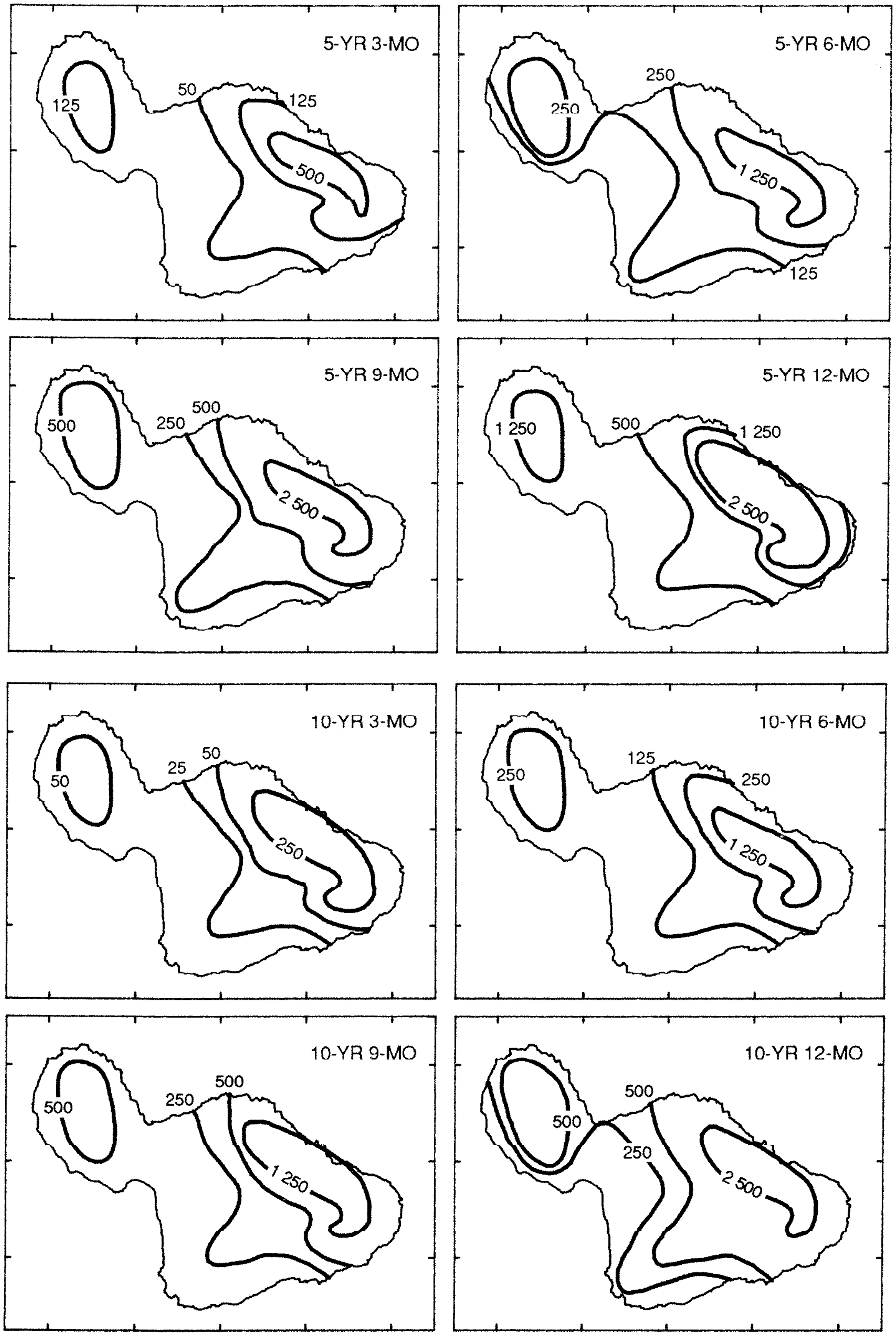


Appendix Figure D.1.—*Continued*



Appendix Figure D.2. Minimum rainfall for 3-, 6-, 9-, and 12-mo durations and 2-, 3-, 5-, 10-, 20-, 30-, 50-, 100-, and 200-yr return periods, Maui Island



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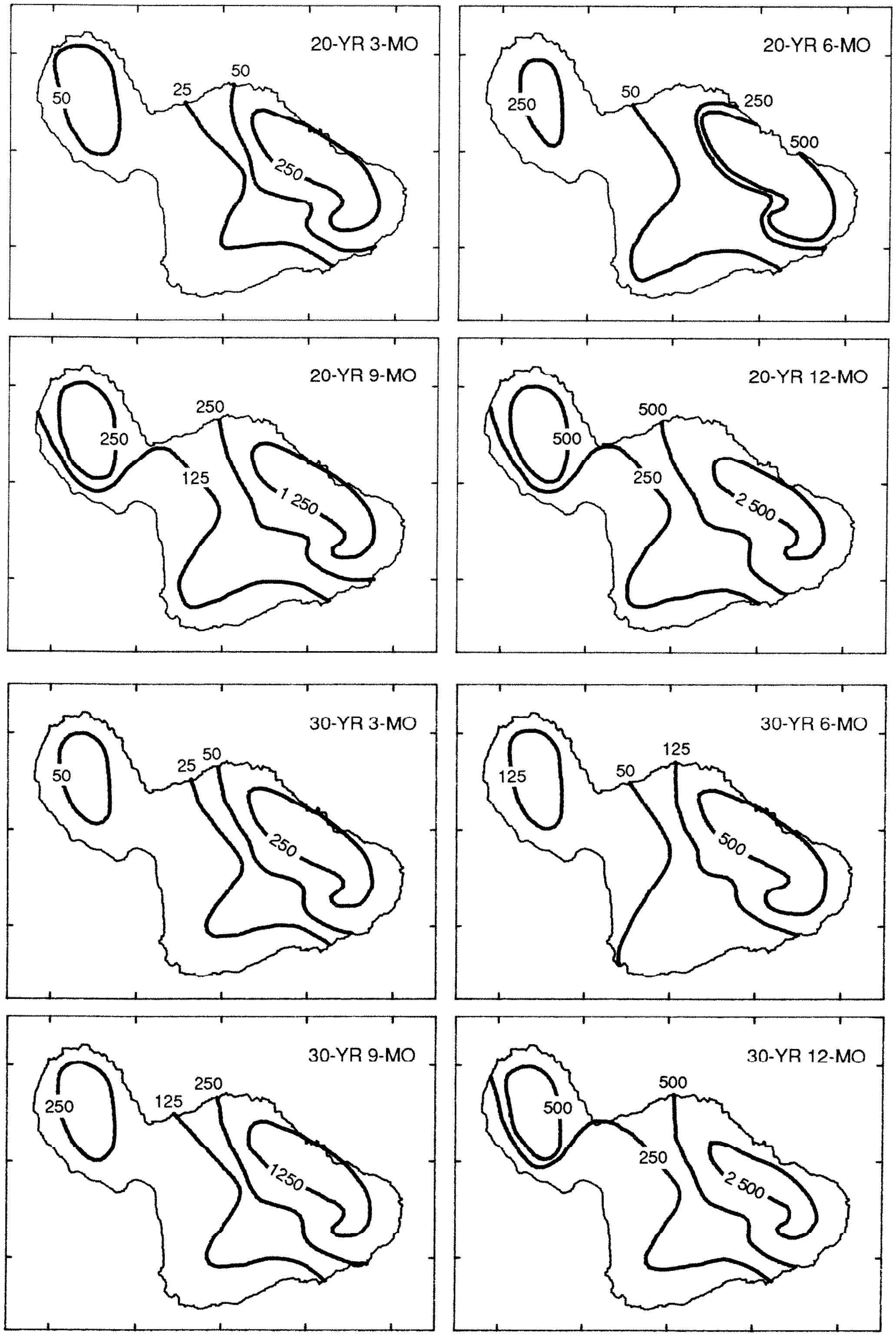

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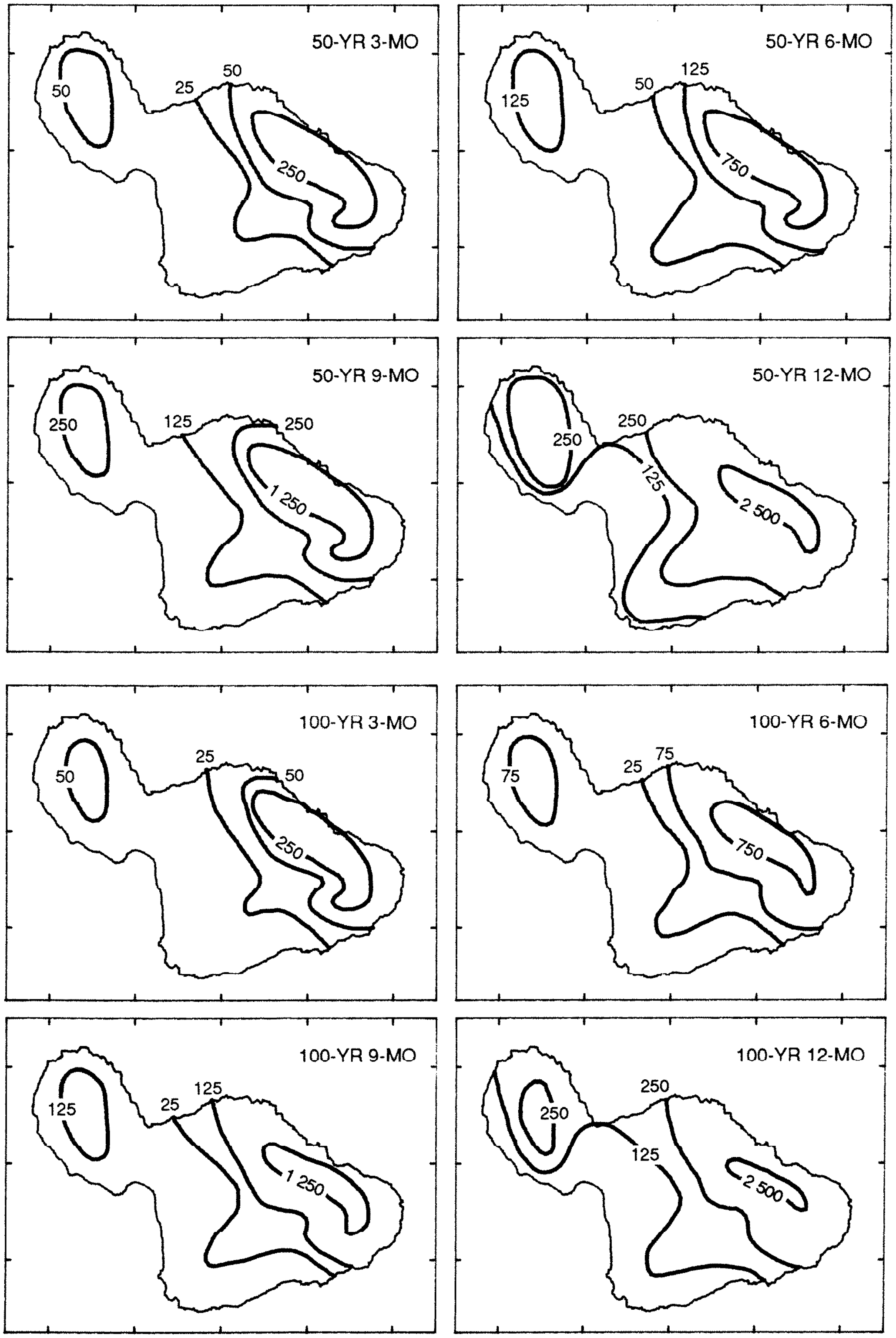

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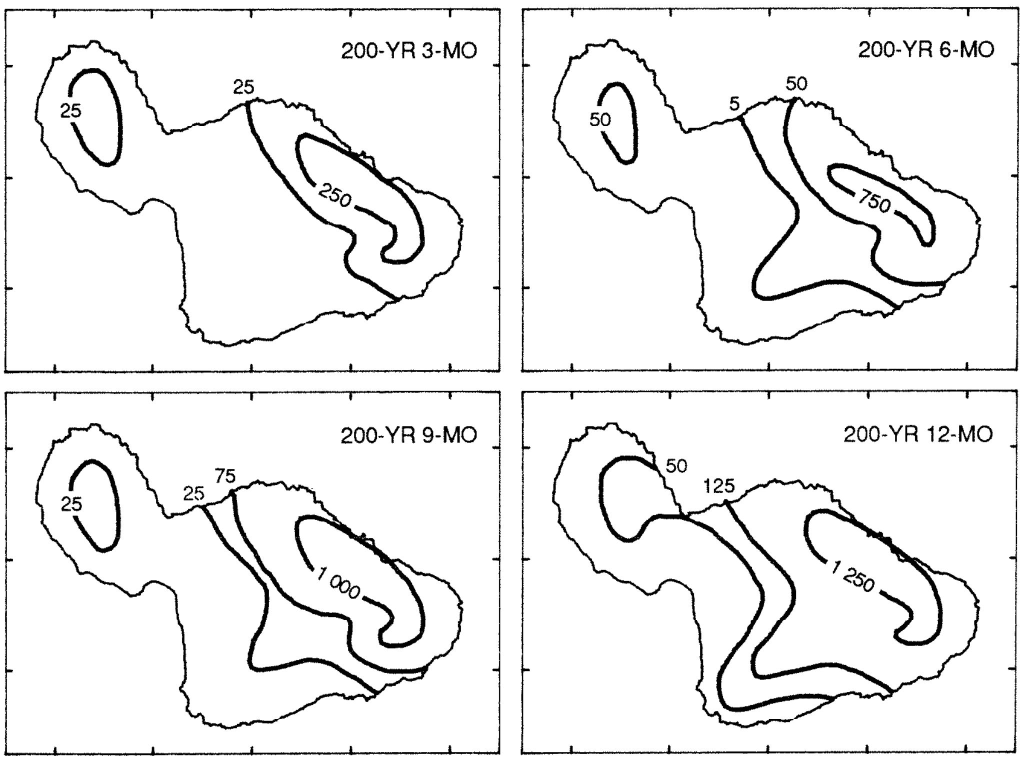

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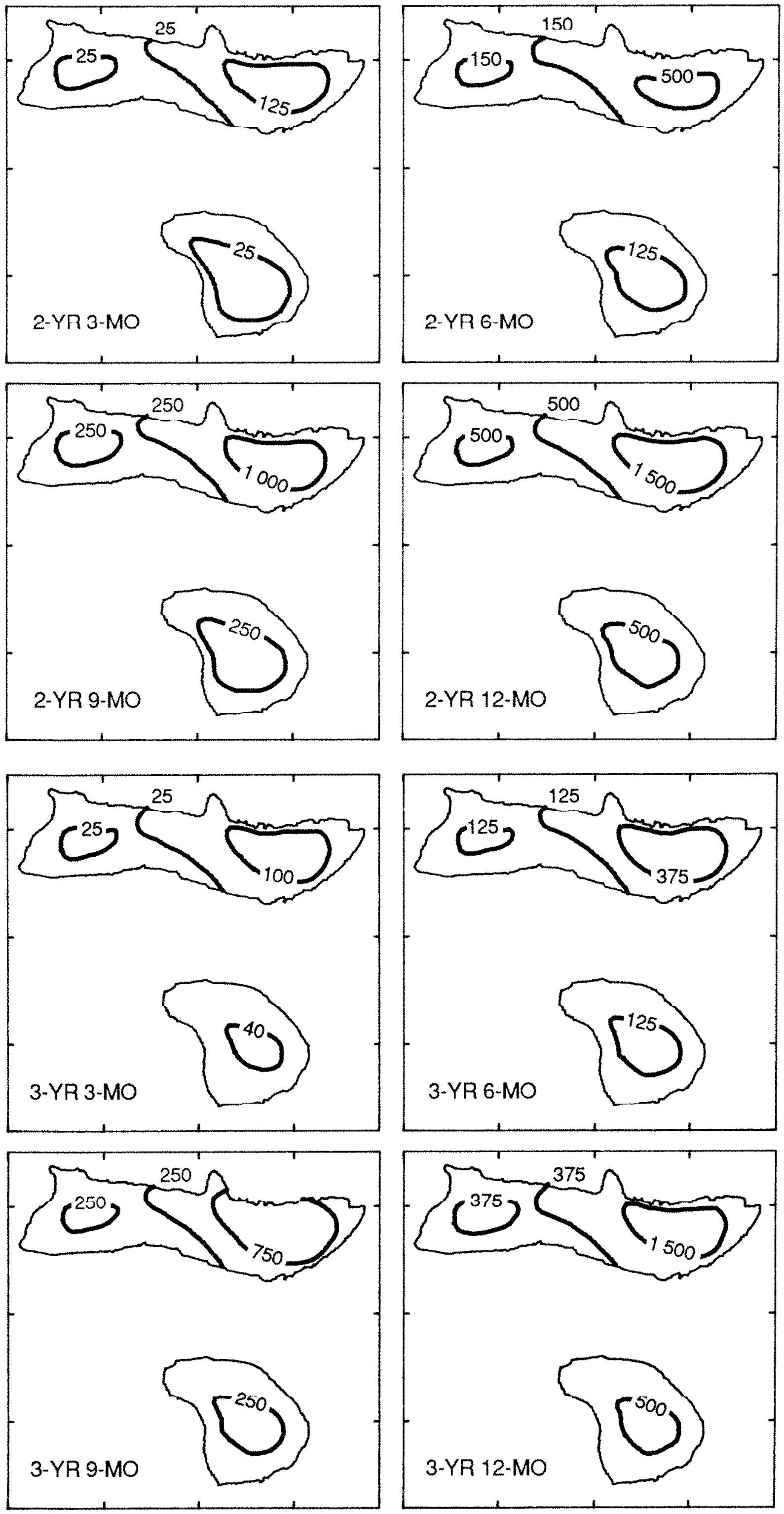
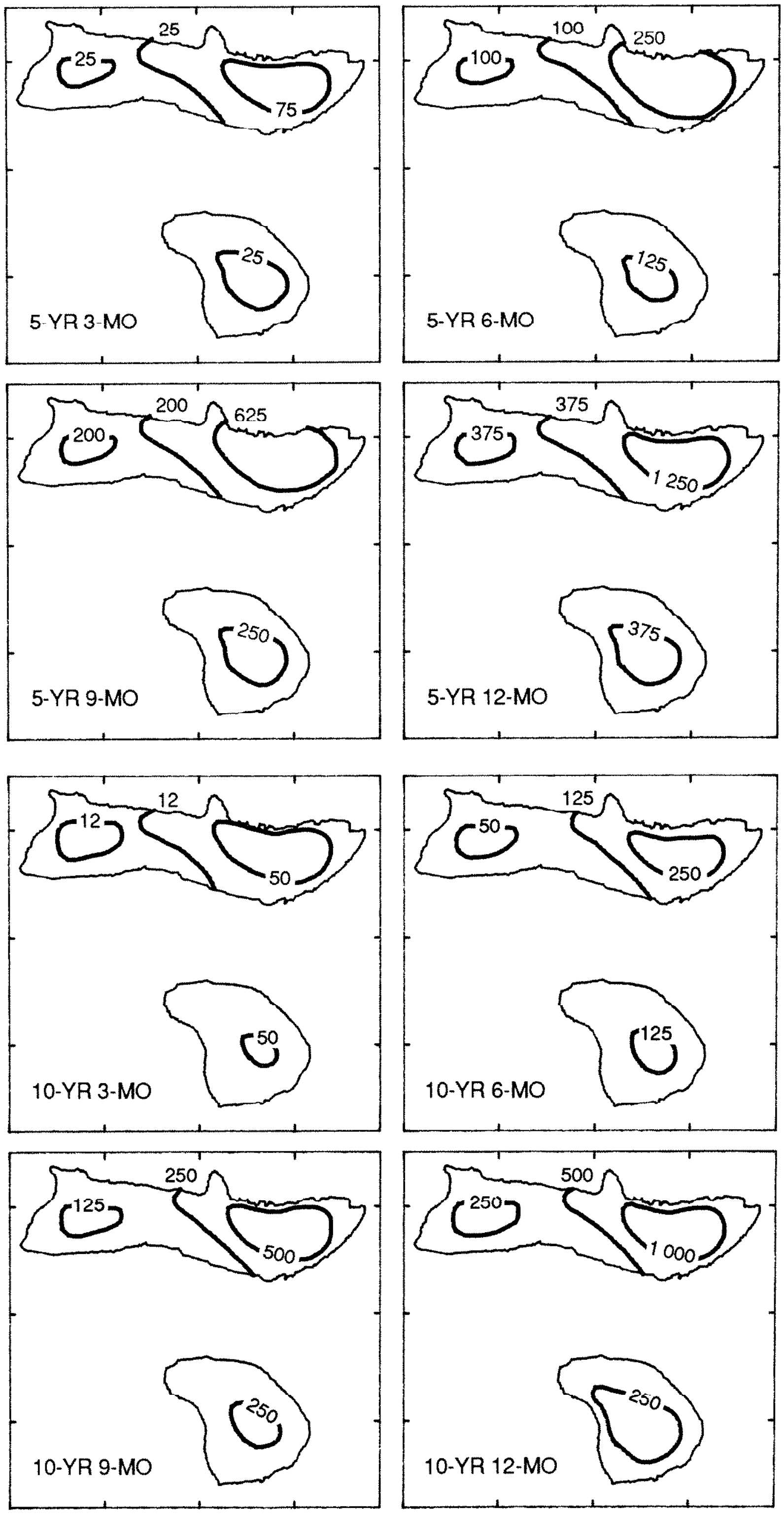


Appendix Figure D.3. Minimum rainfall for 3-, 6-, 9-, and 12-mo durations and 2-, 3-, 5-, 10-, 20-, 30-, 50-, 100-, and 200-yr return periods, Moloka'i and Lāna'i Island



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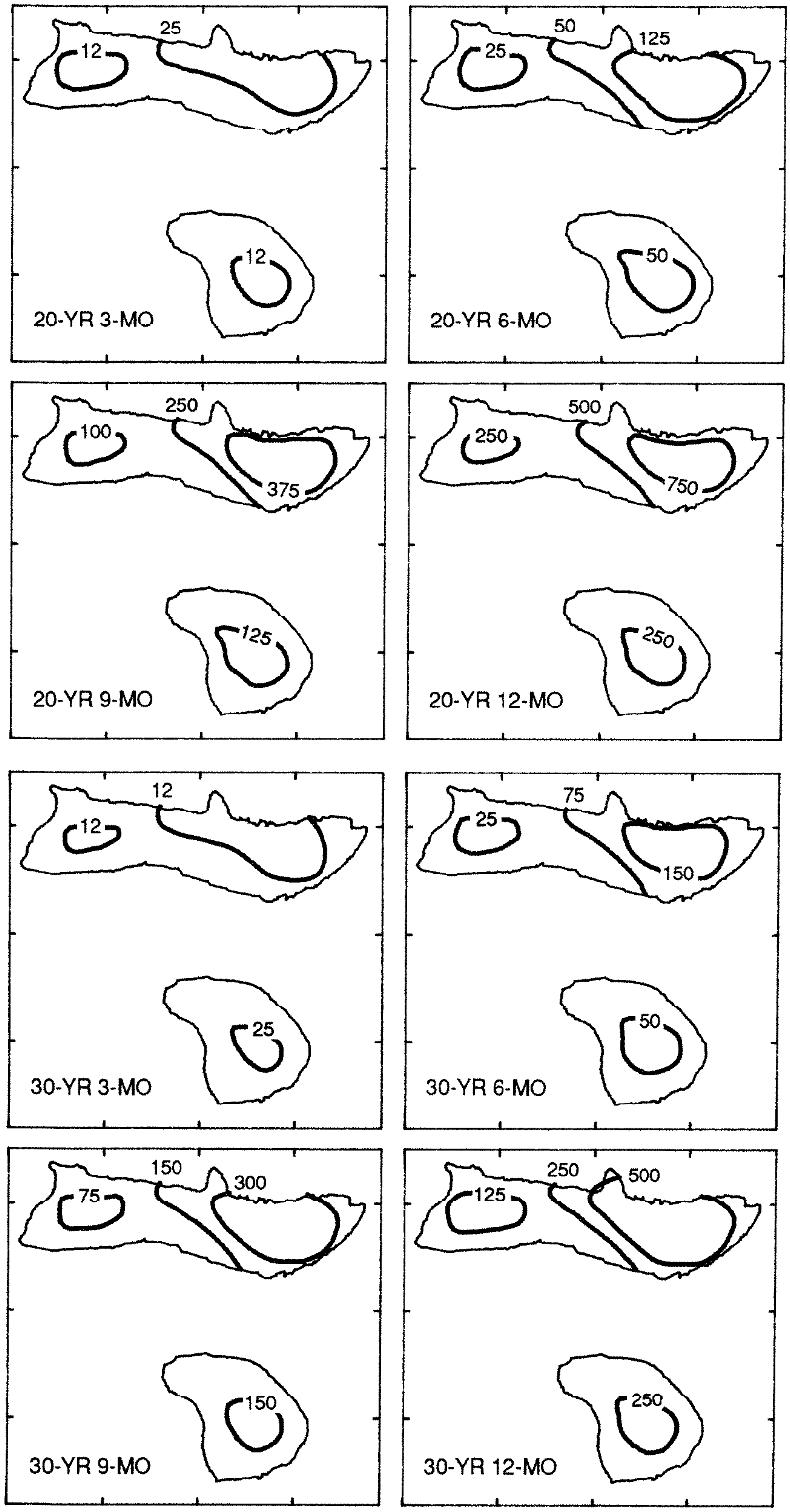

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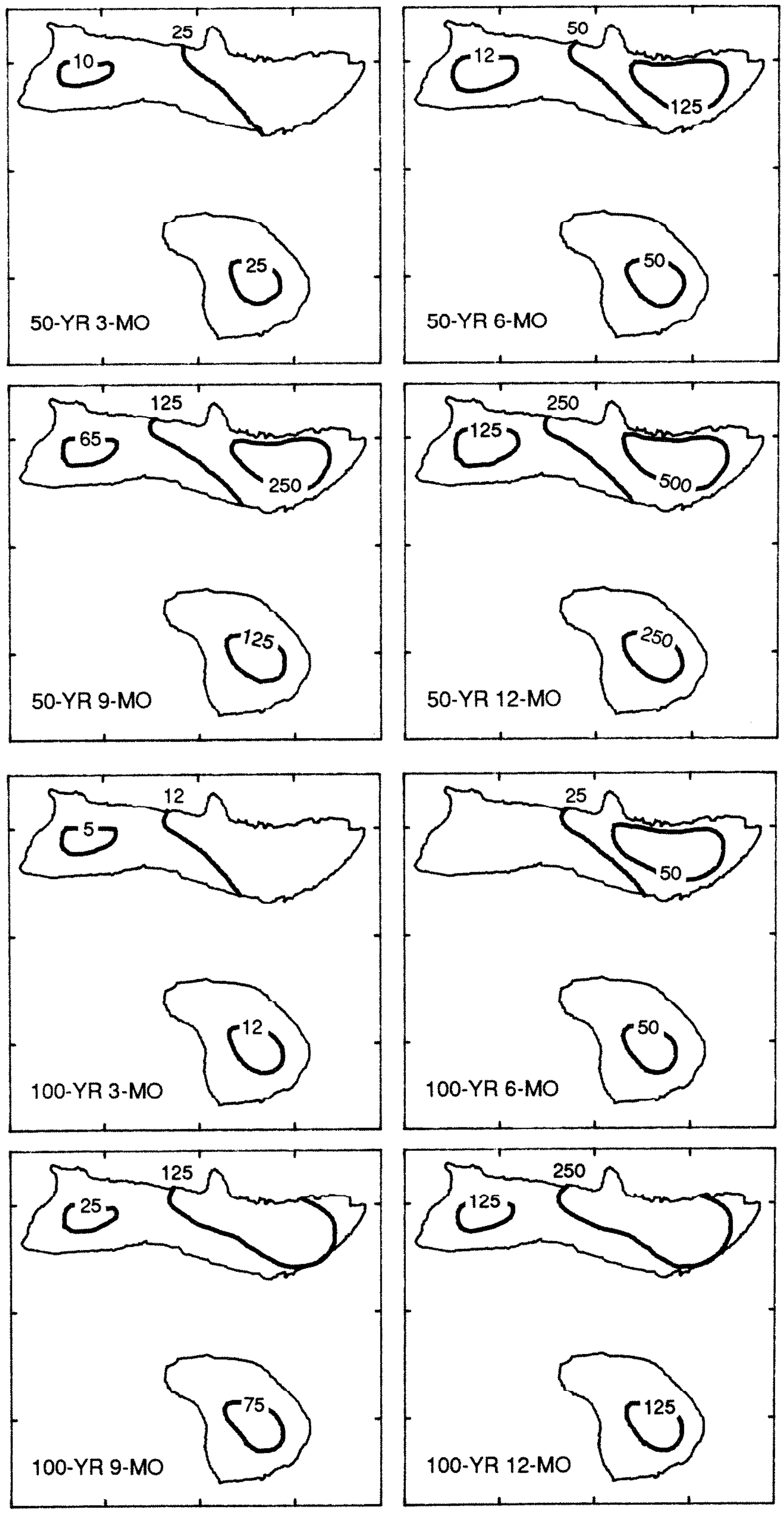

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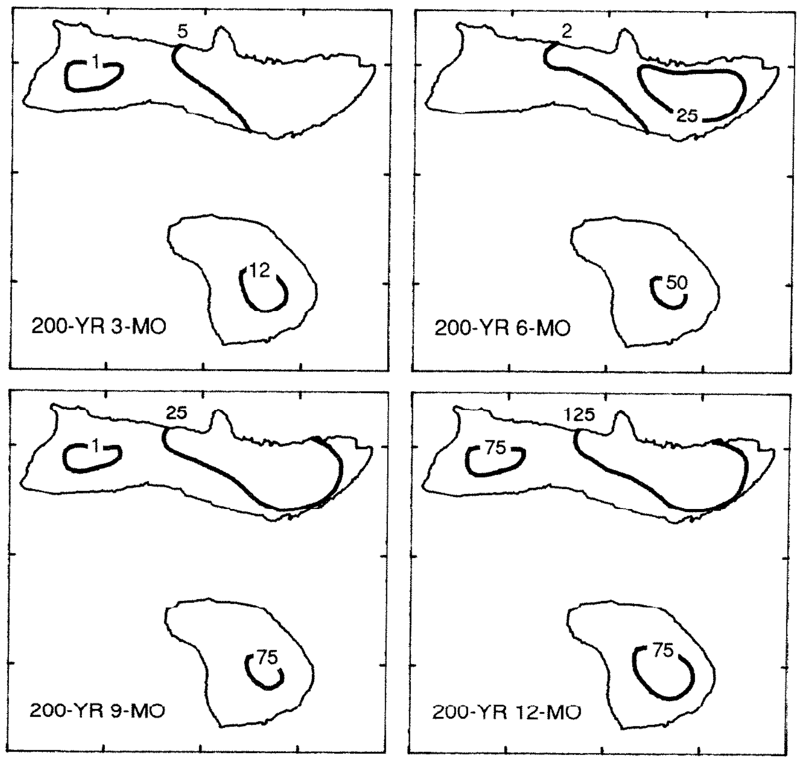

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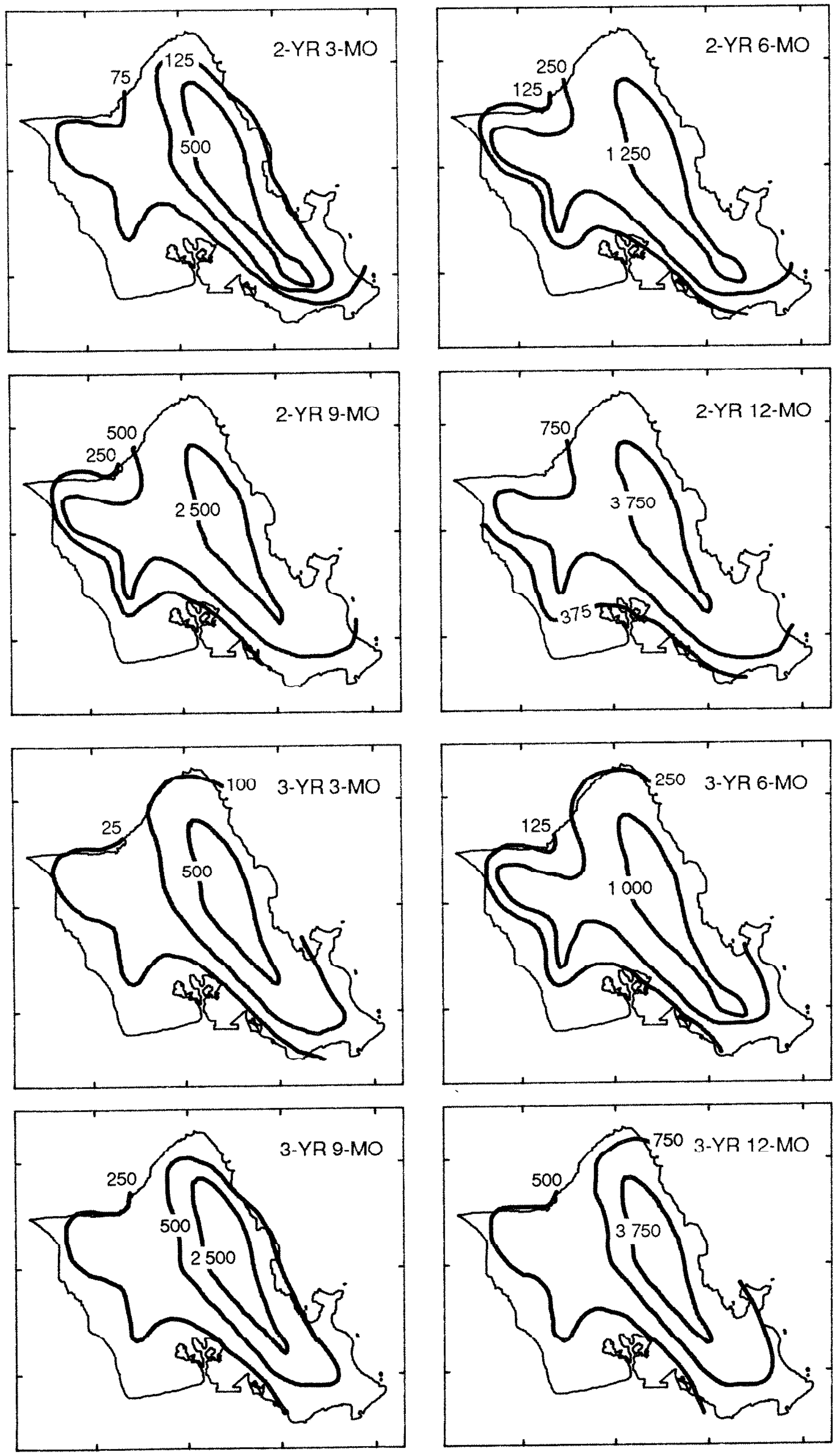
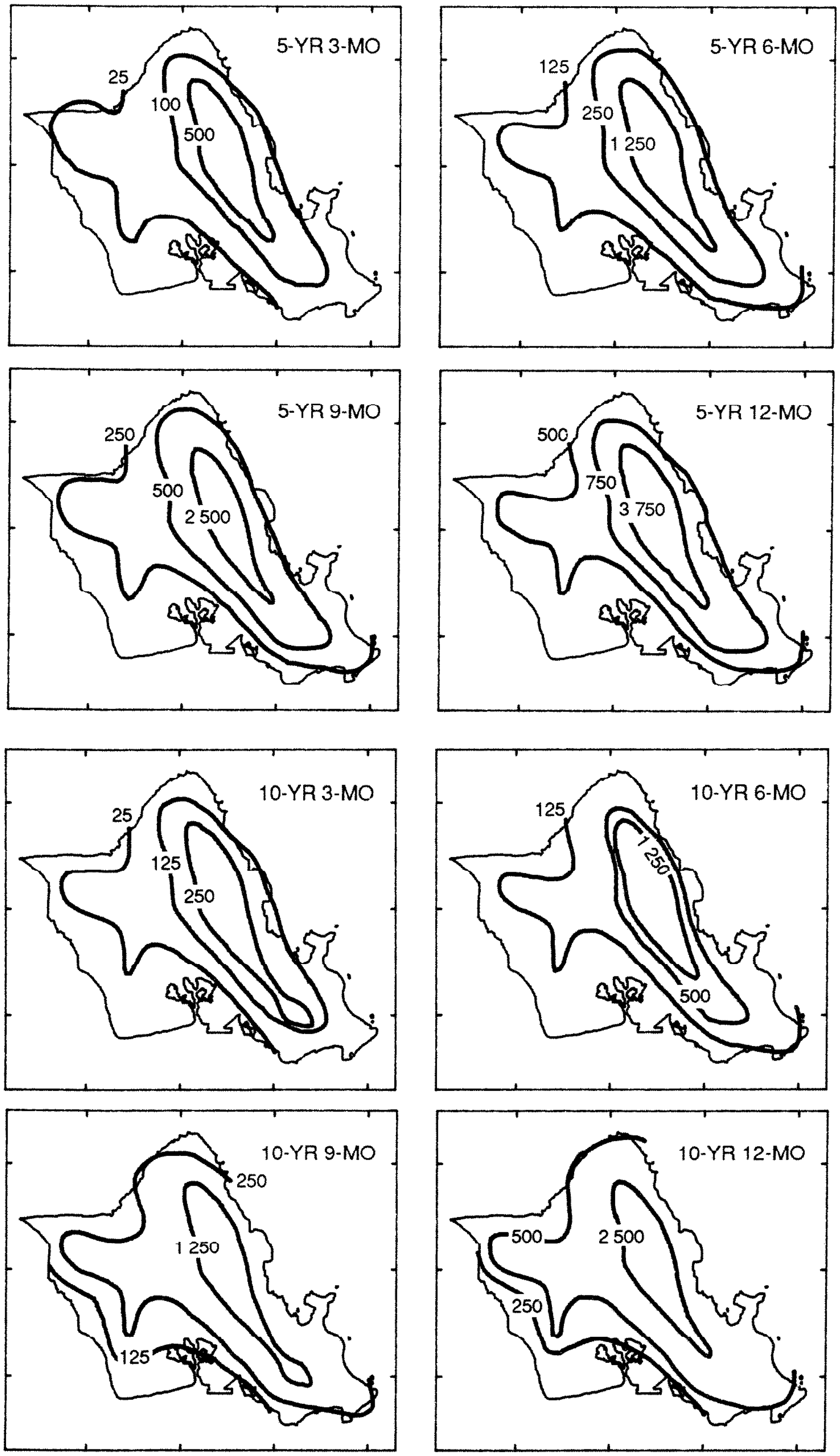


Appendix Figure D.4. Minimum rainfall for 3-, 6-, 9-, and 12-mo durations and 2-, 3-, 5-, 10-, 20-, 30-, 50-, 100-, and 200-yr return periods, O'ahu Island



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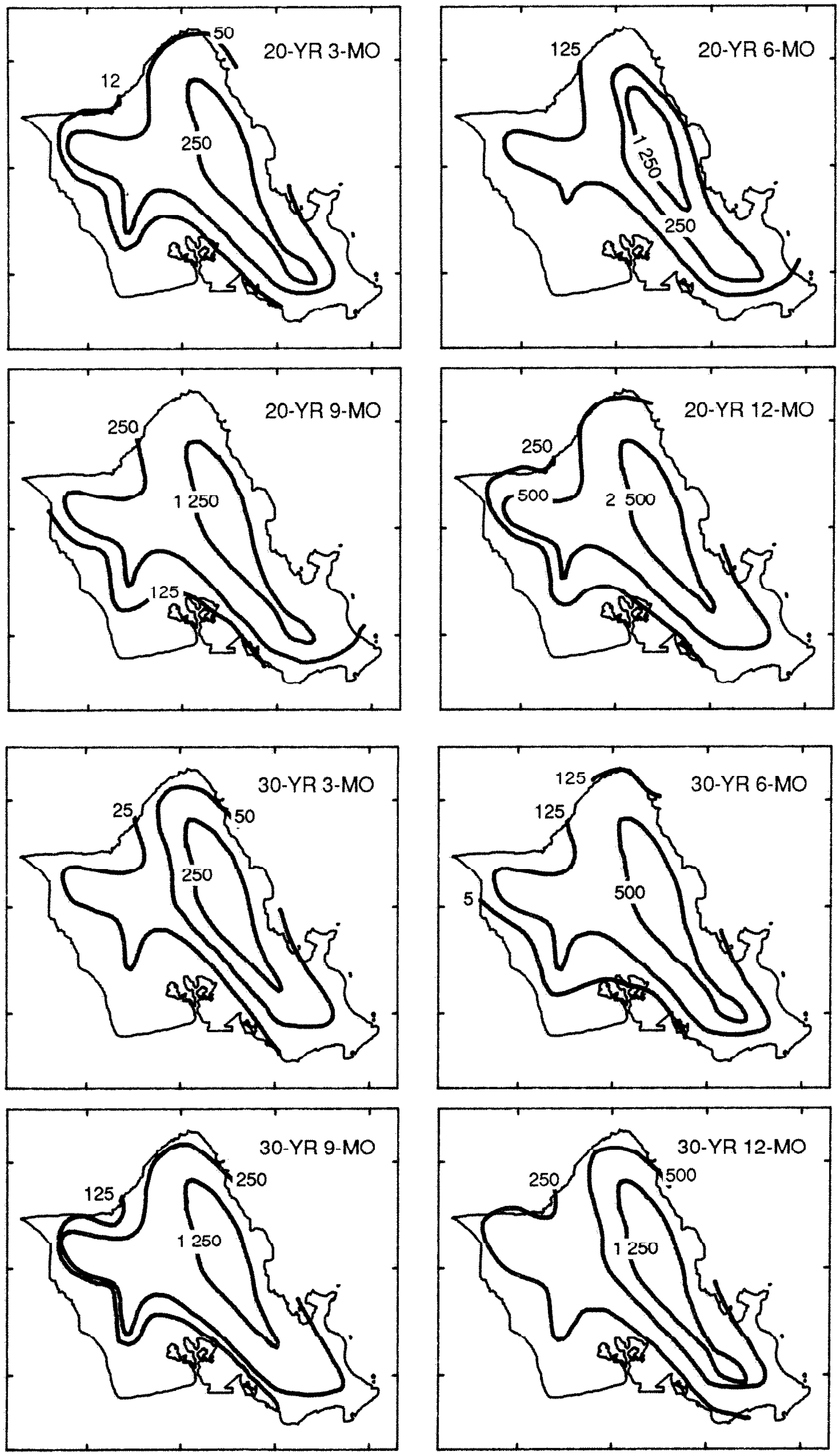

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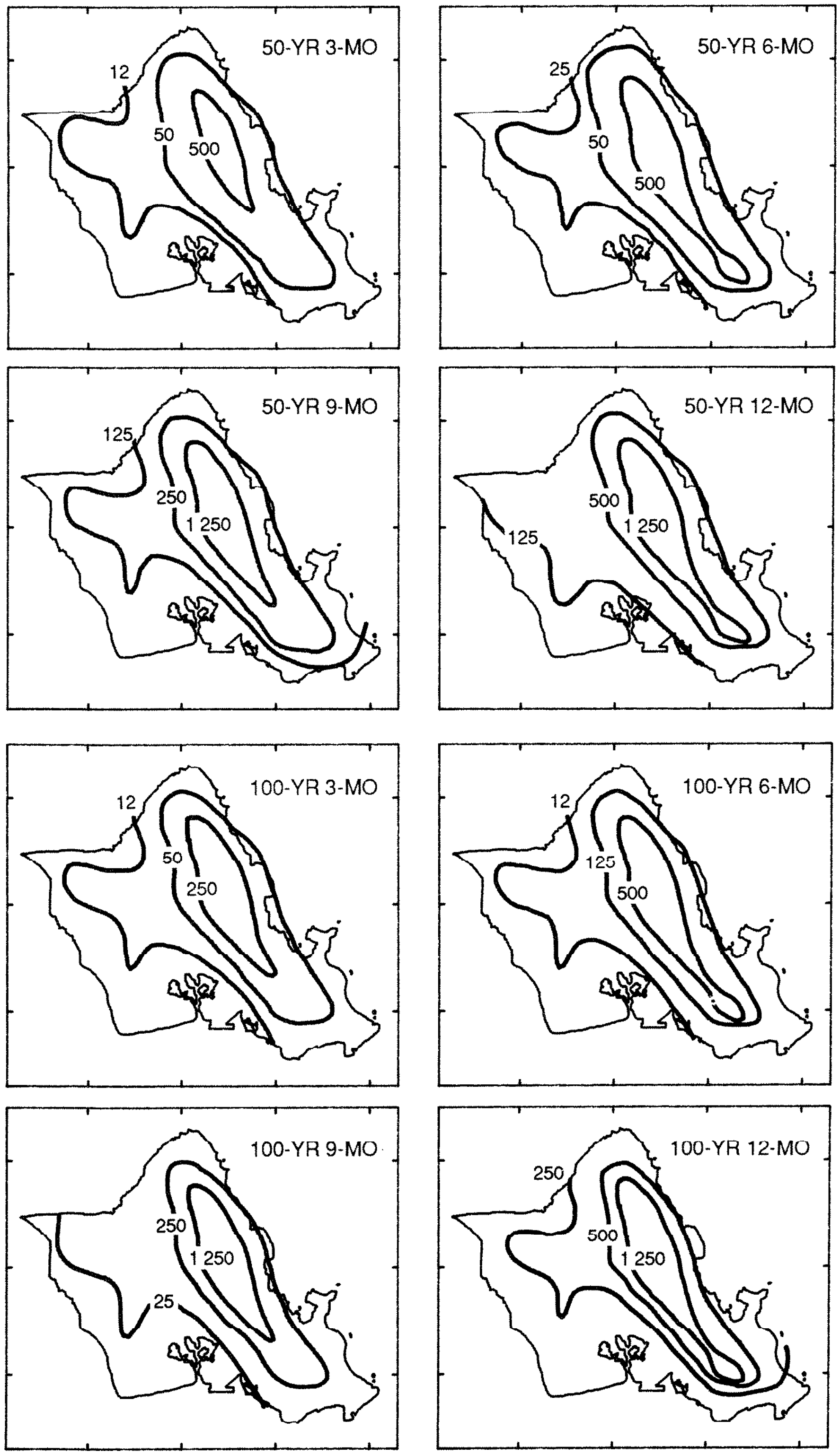

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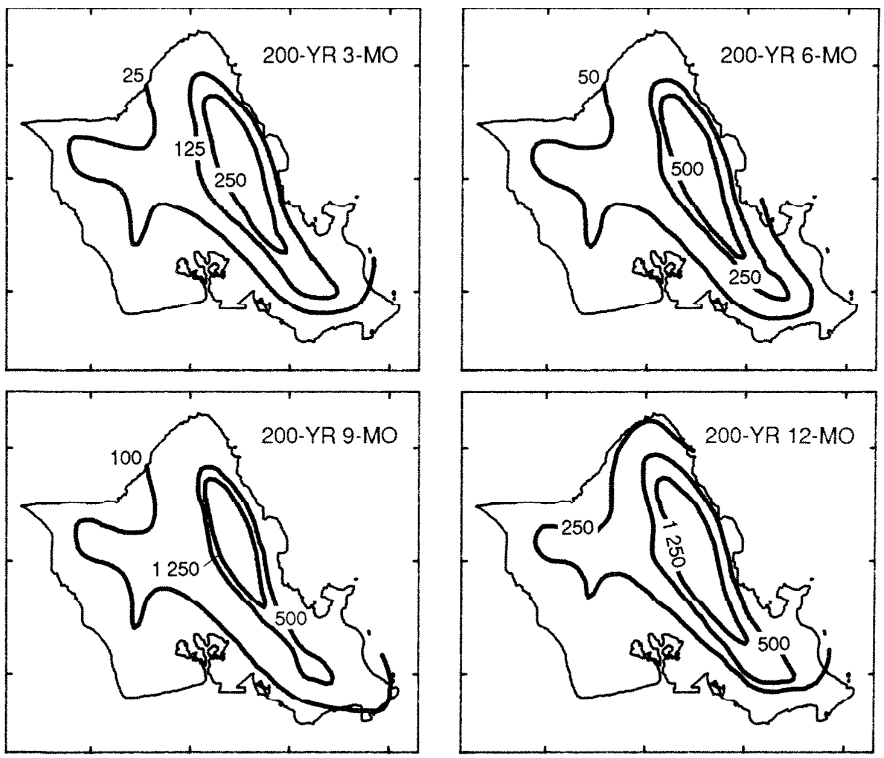

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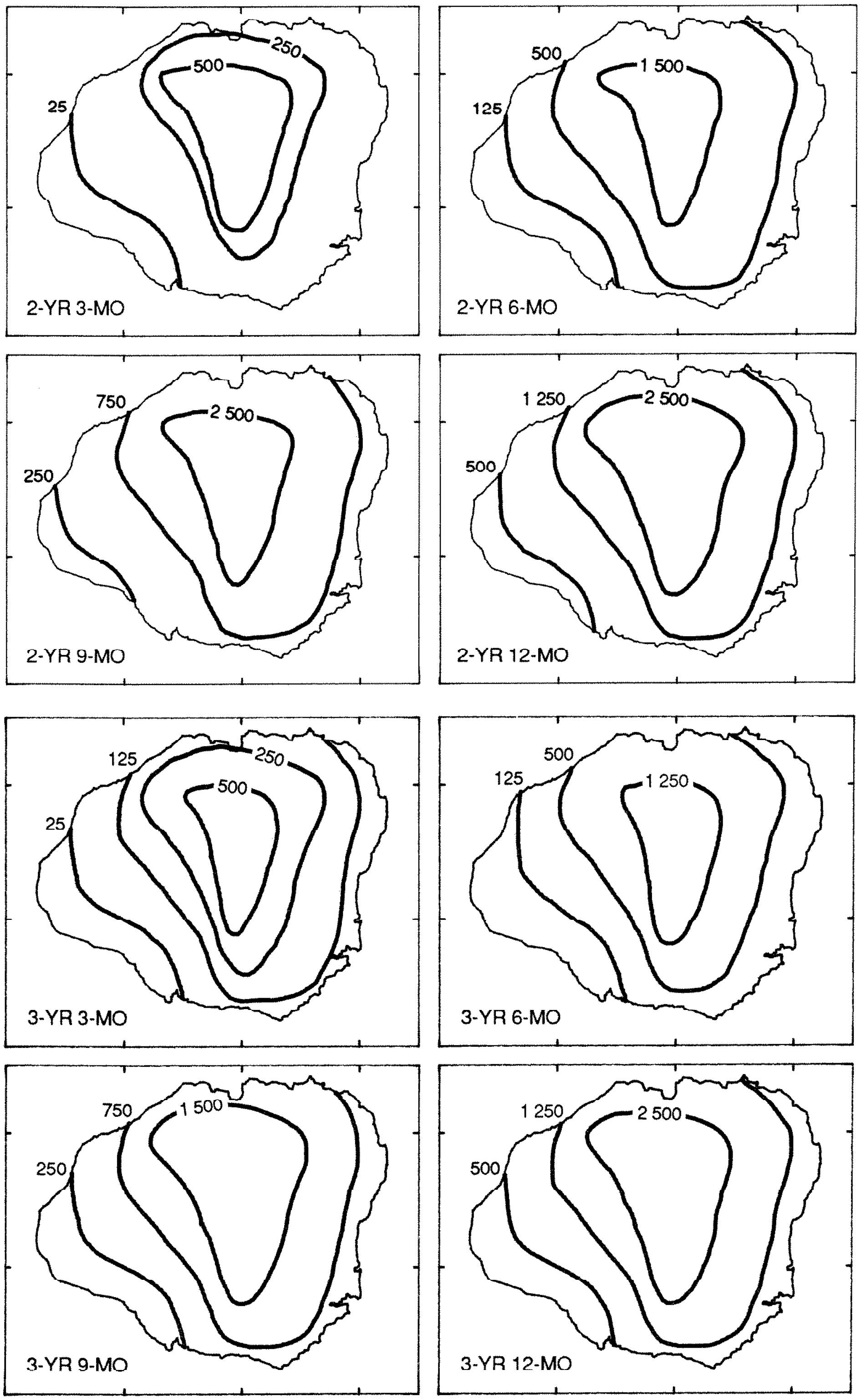
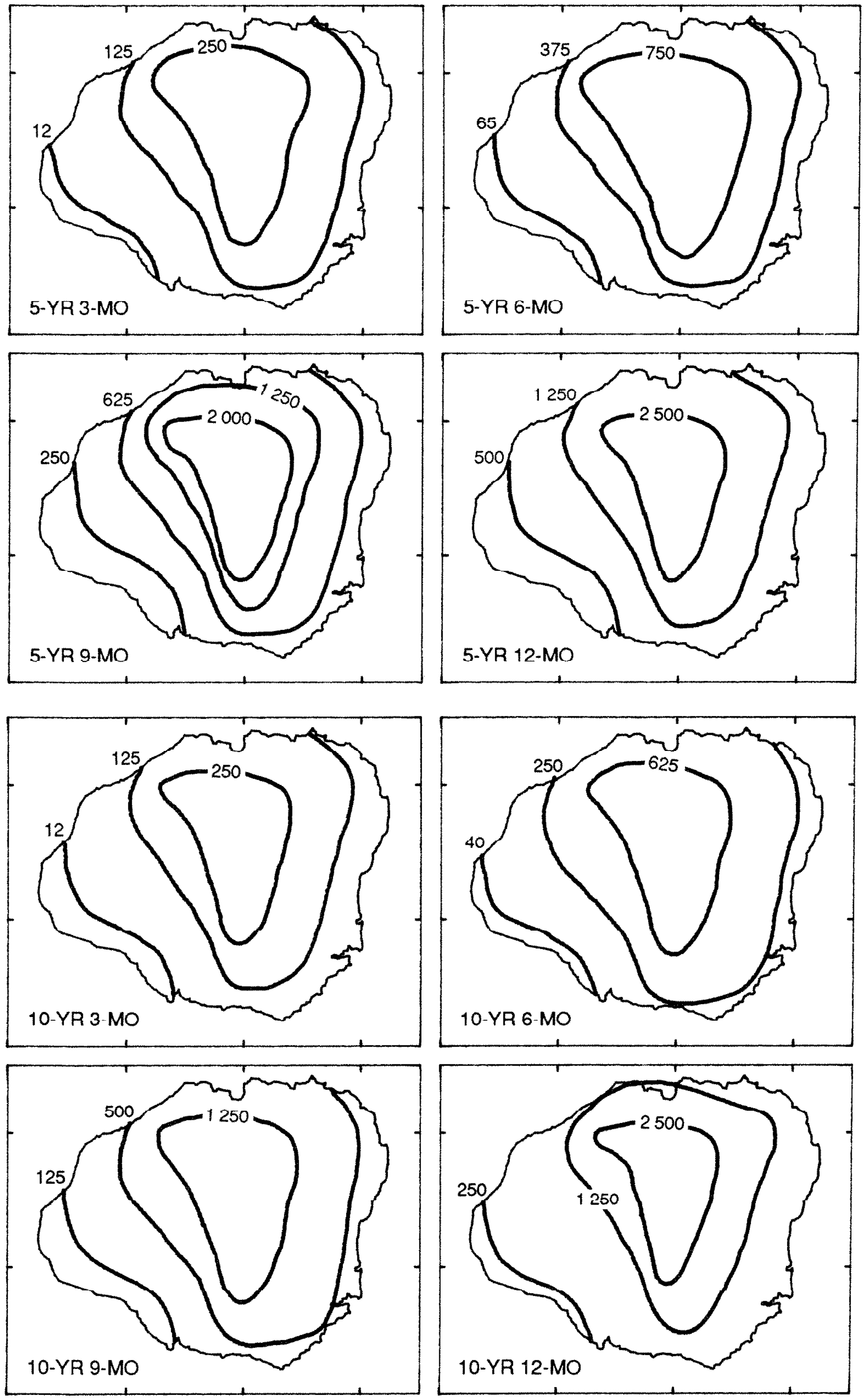


Appendix Figure D.5. Minimum rainfall for 3-, 6-, 9-, and 12-mo durations and 2-, 3-, 5-, 10-, 20-, 30-, 50-, 100-, and 200-yr return periods, Kaua'i Island



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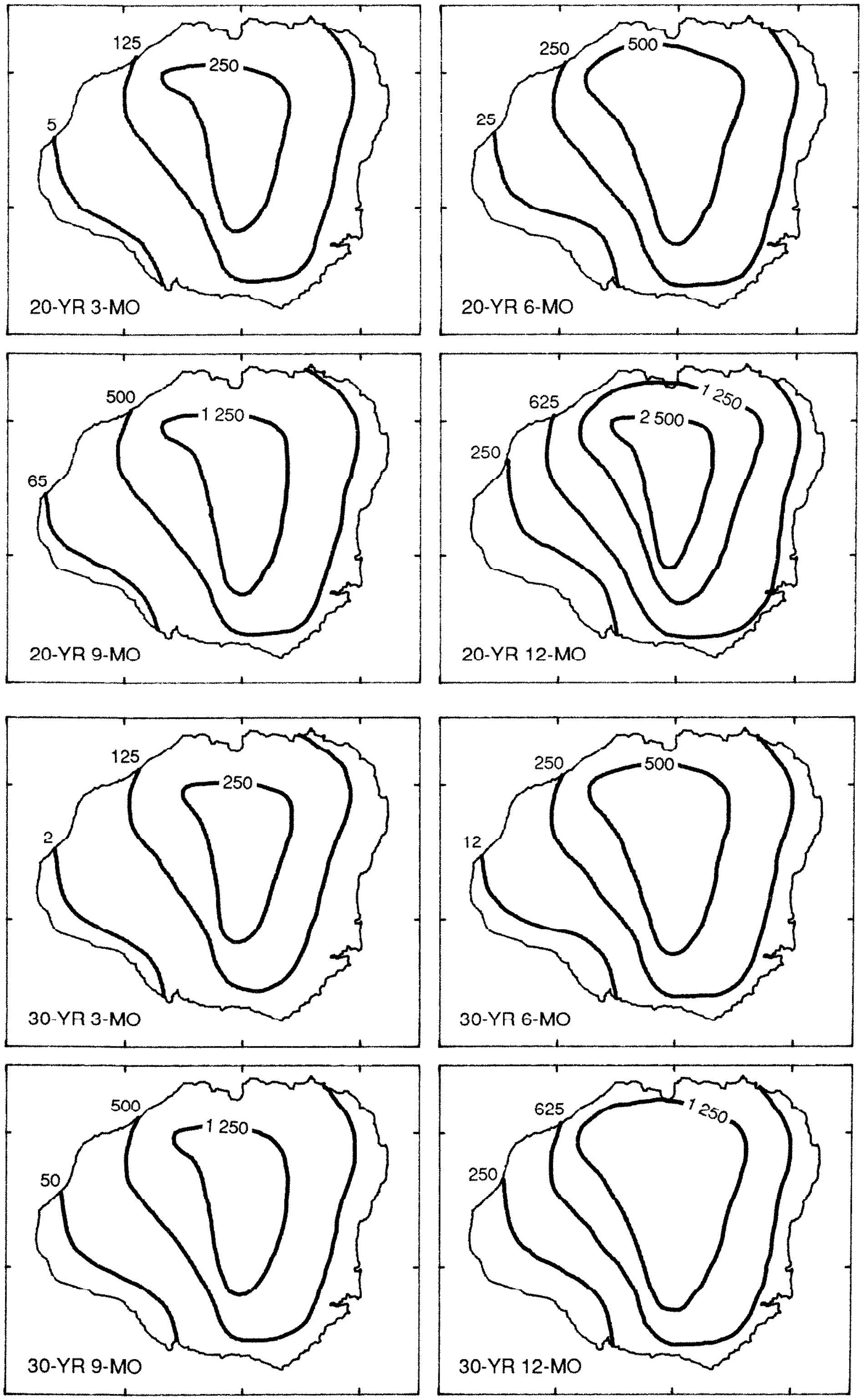

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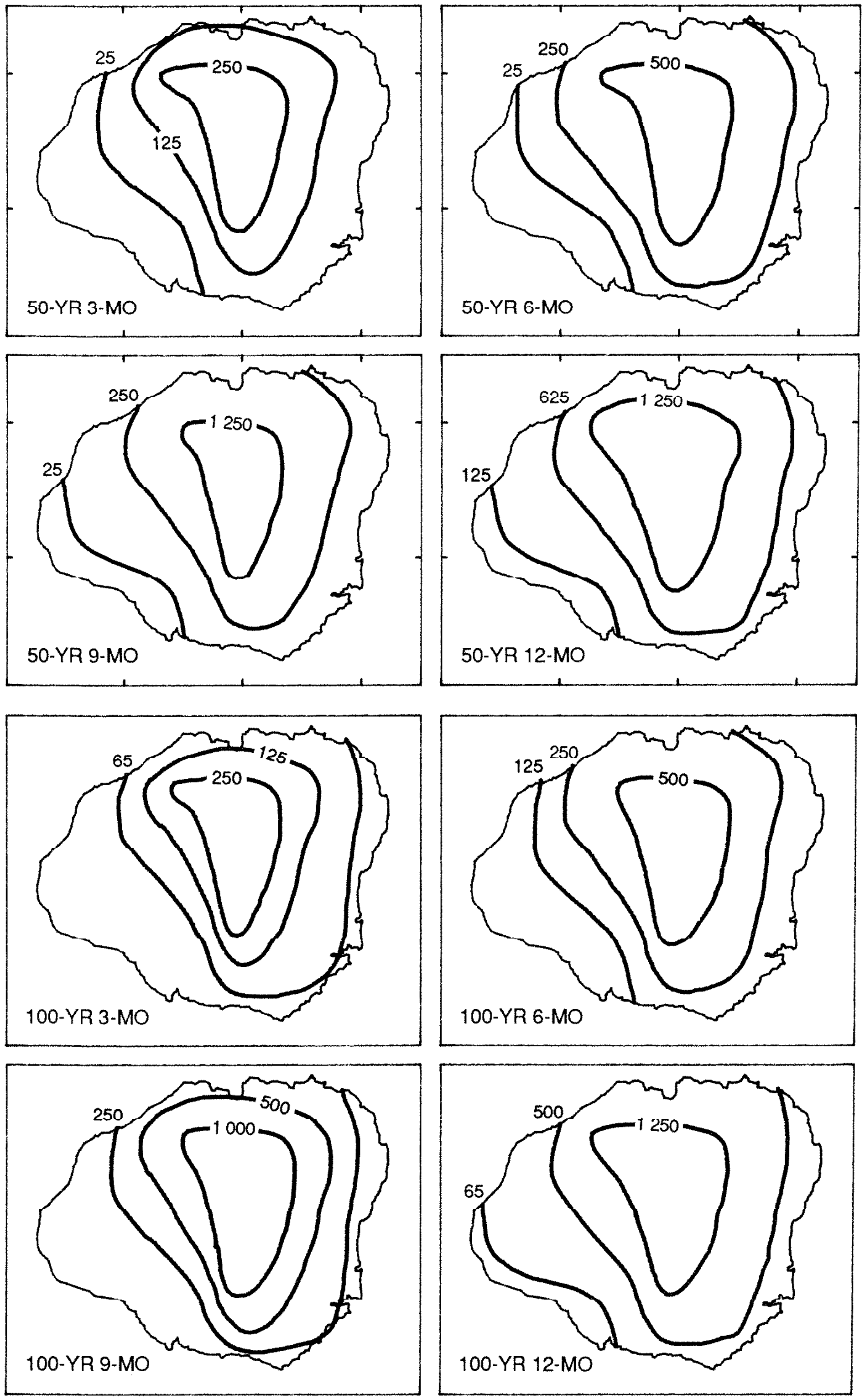

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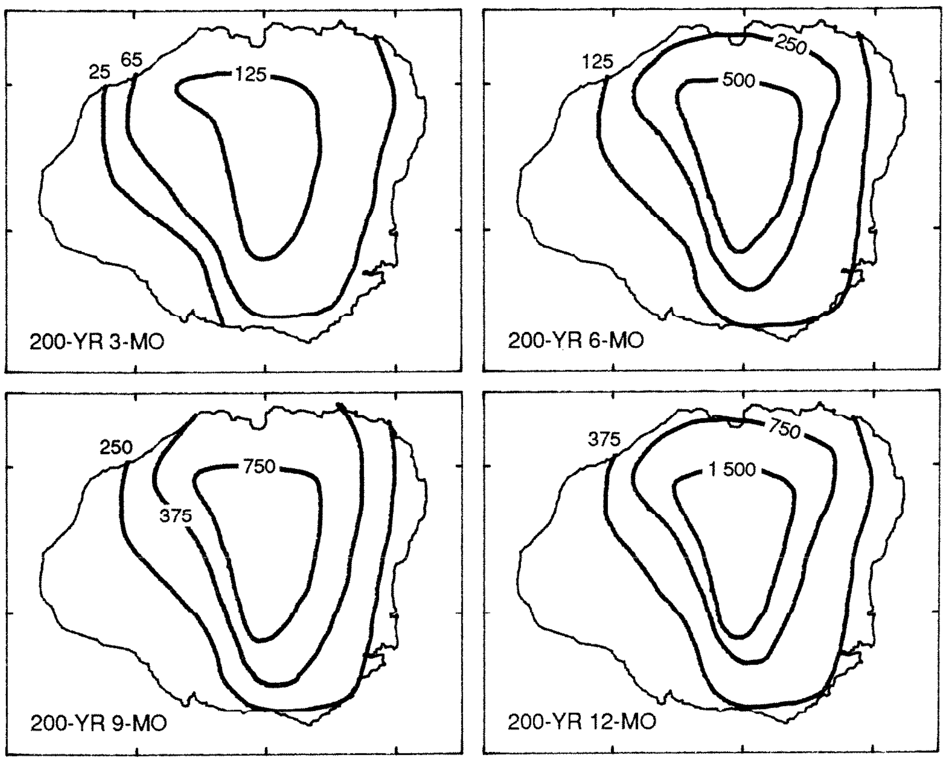

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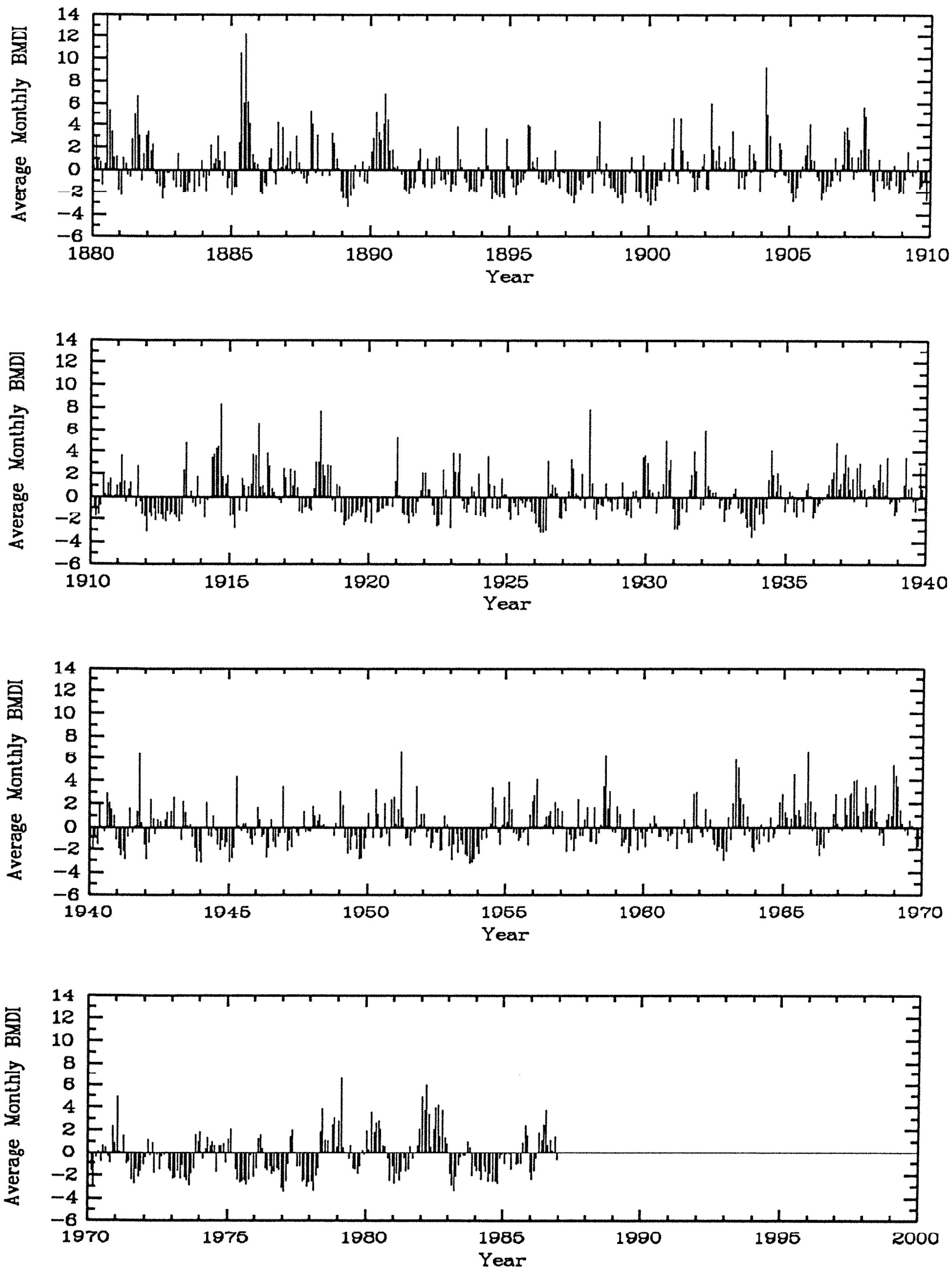
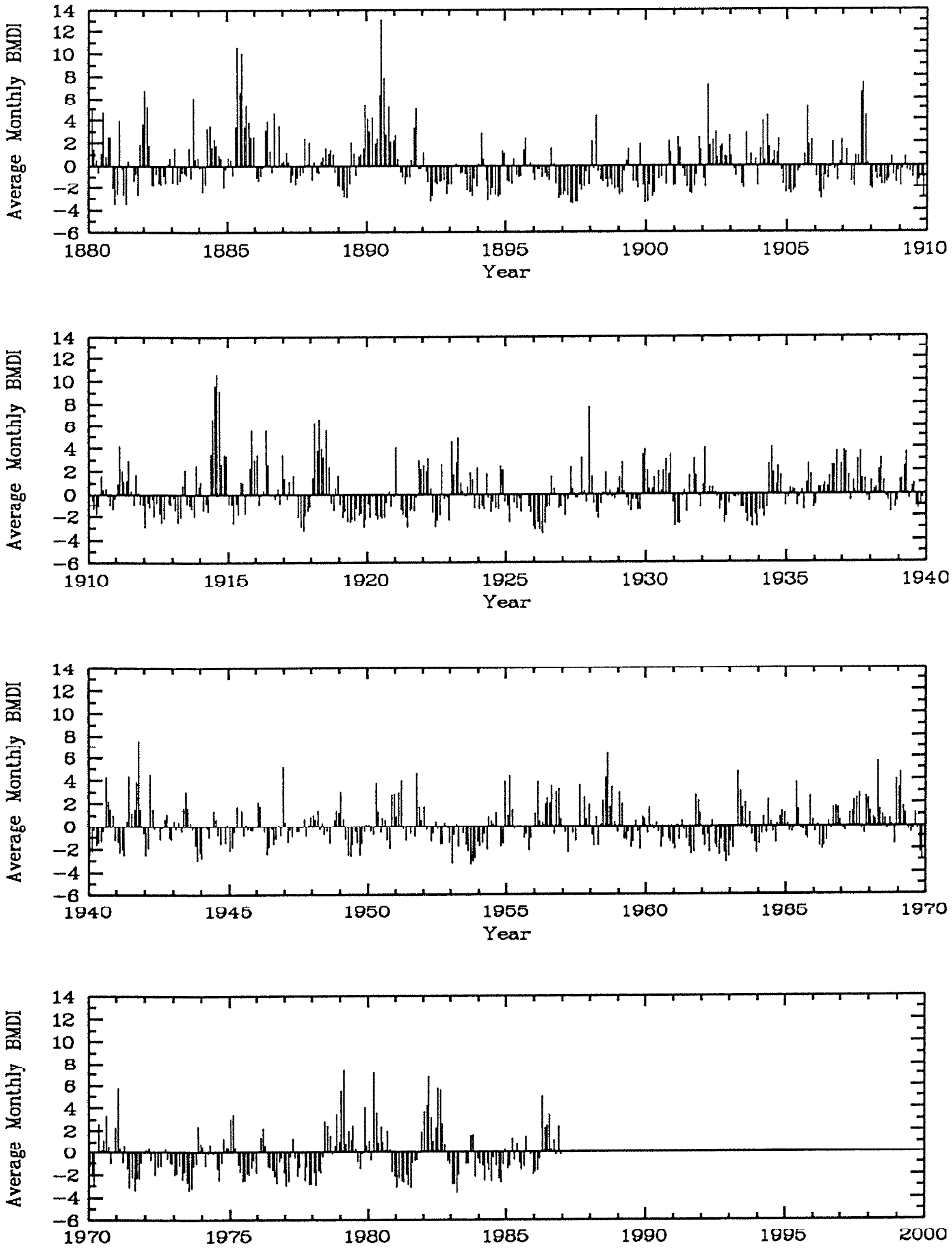
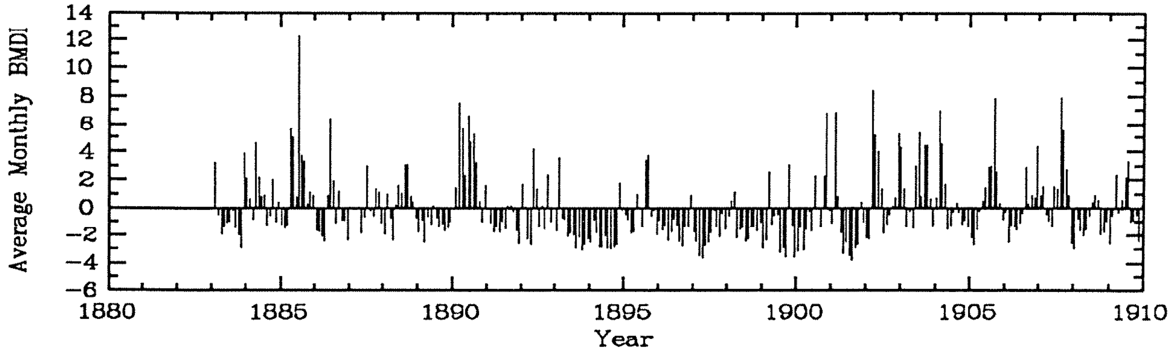
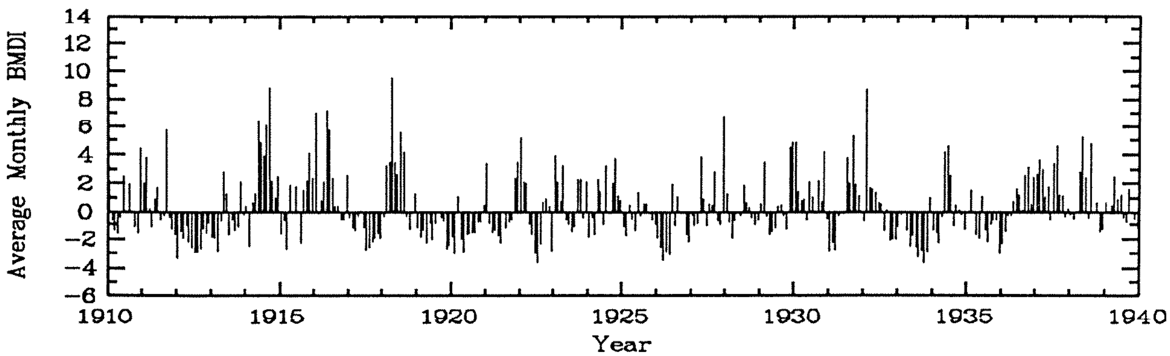


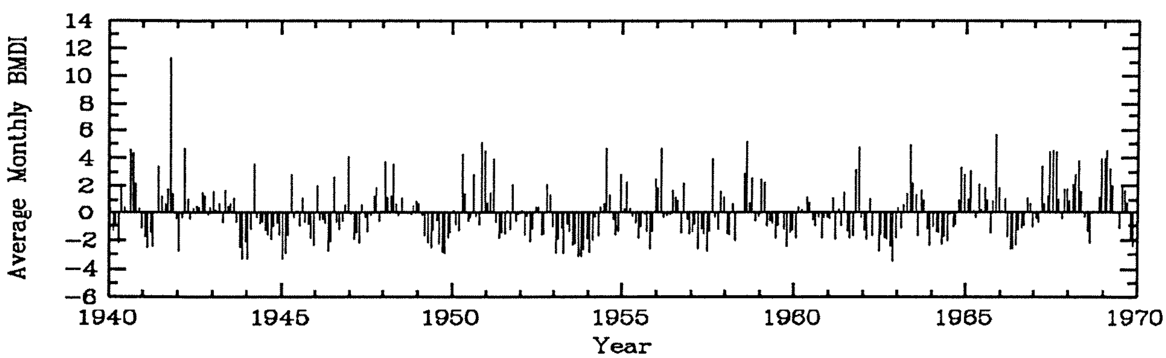
Appendix Figure D.6. Average monthly BMDI time series, Hawai'i State

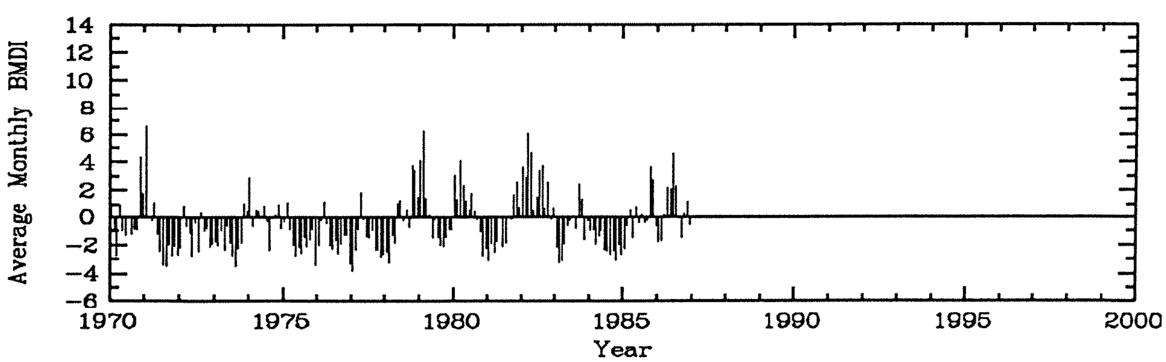


Appendix Figure D.7. Average monthly BMDI time series, Hawai'i Island

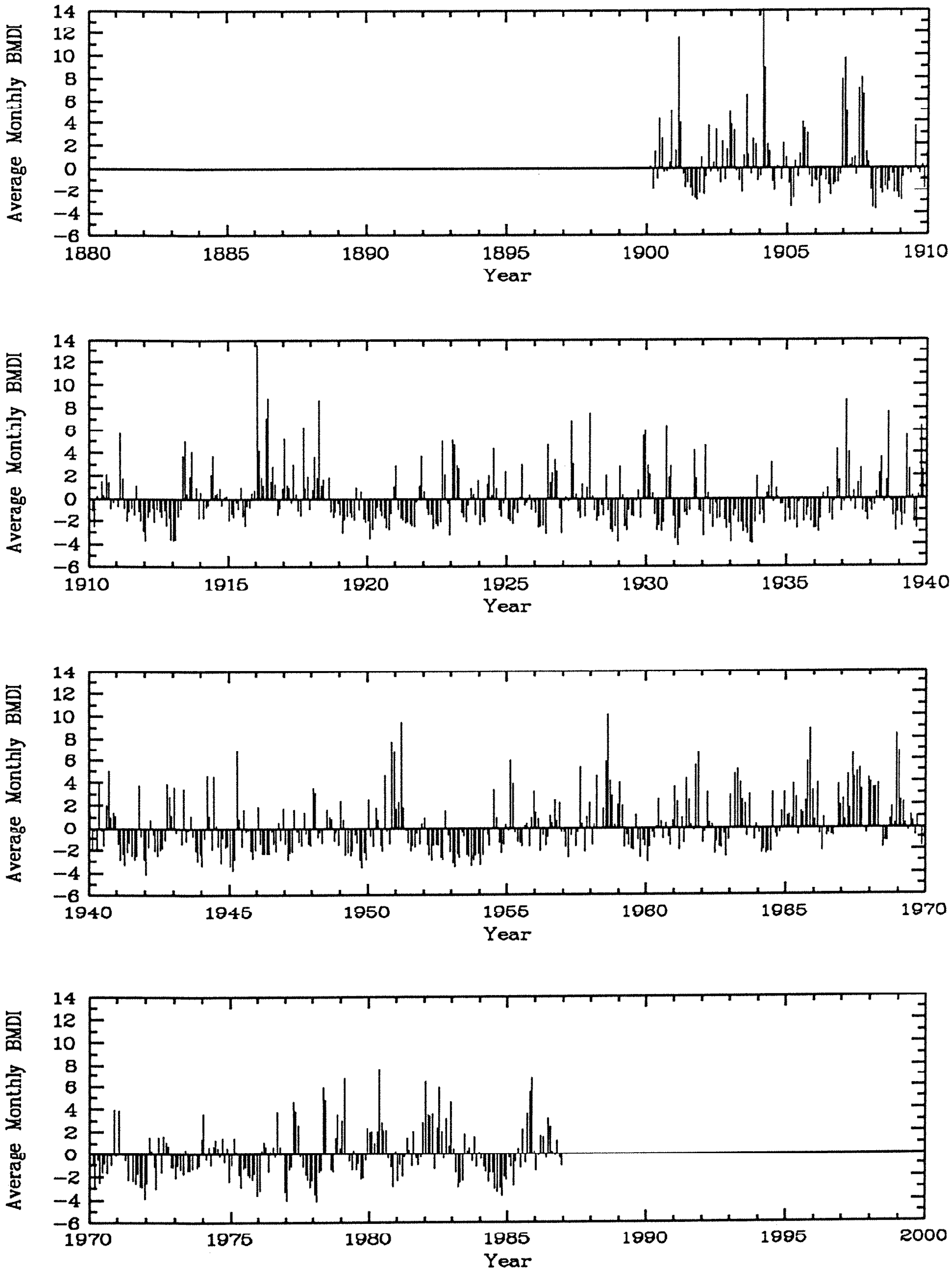




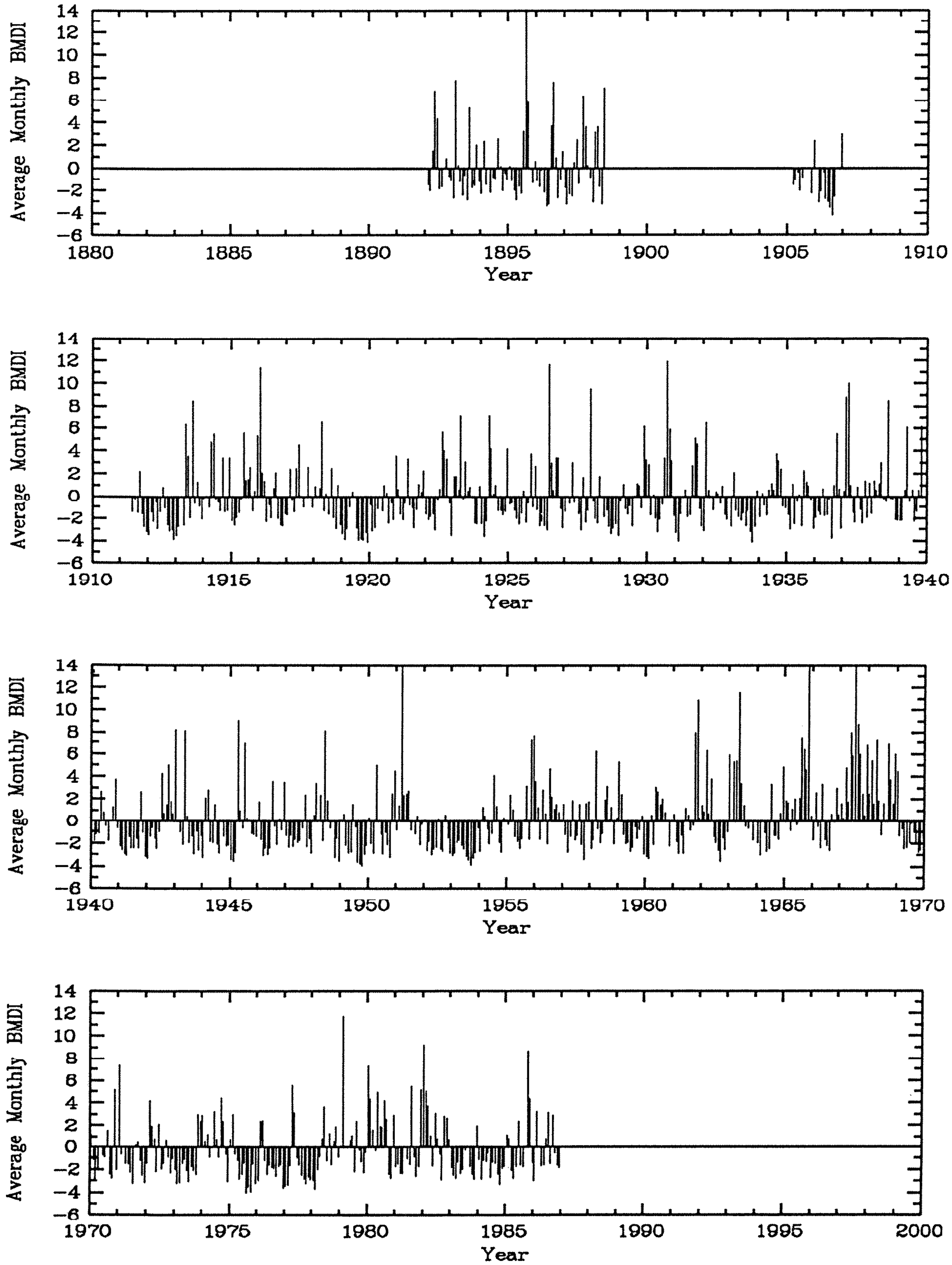




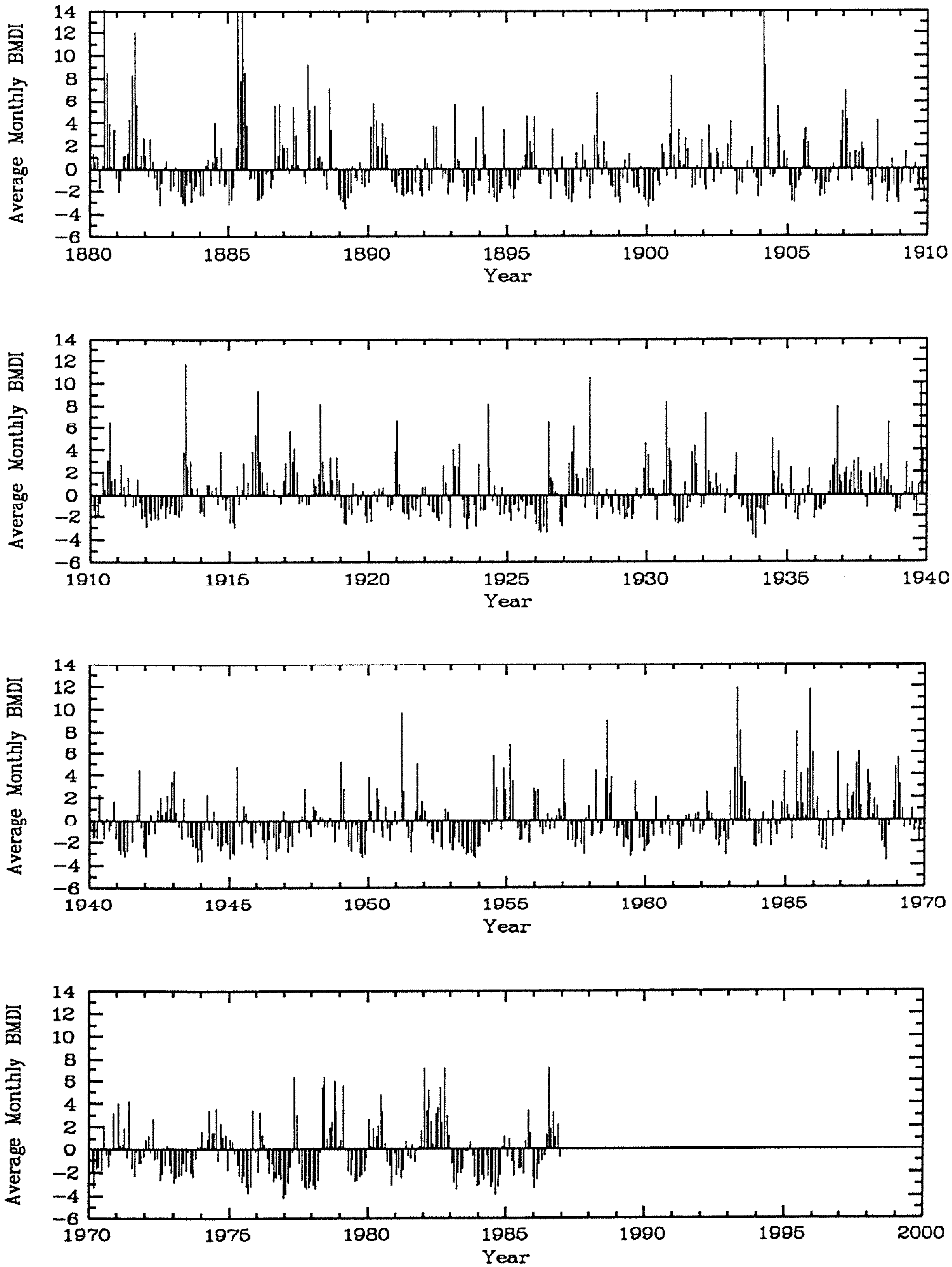
Appendix Figure D.8. Average monthly BMDI time series, Maui Island



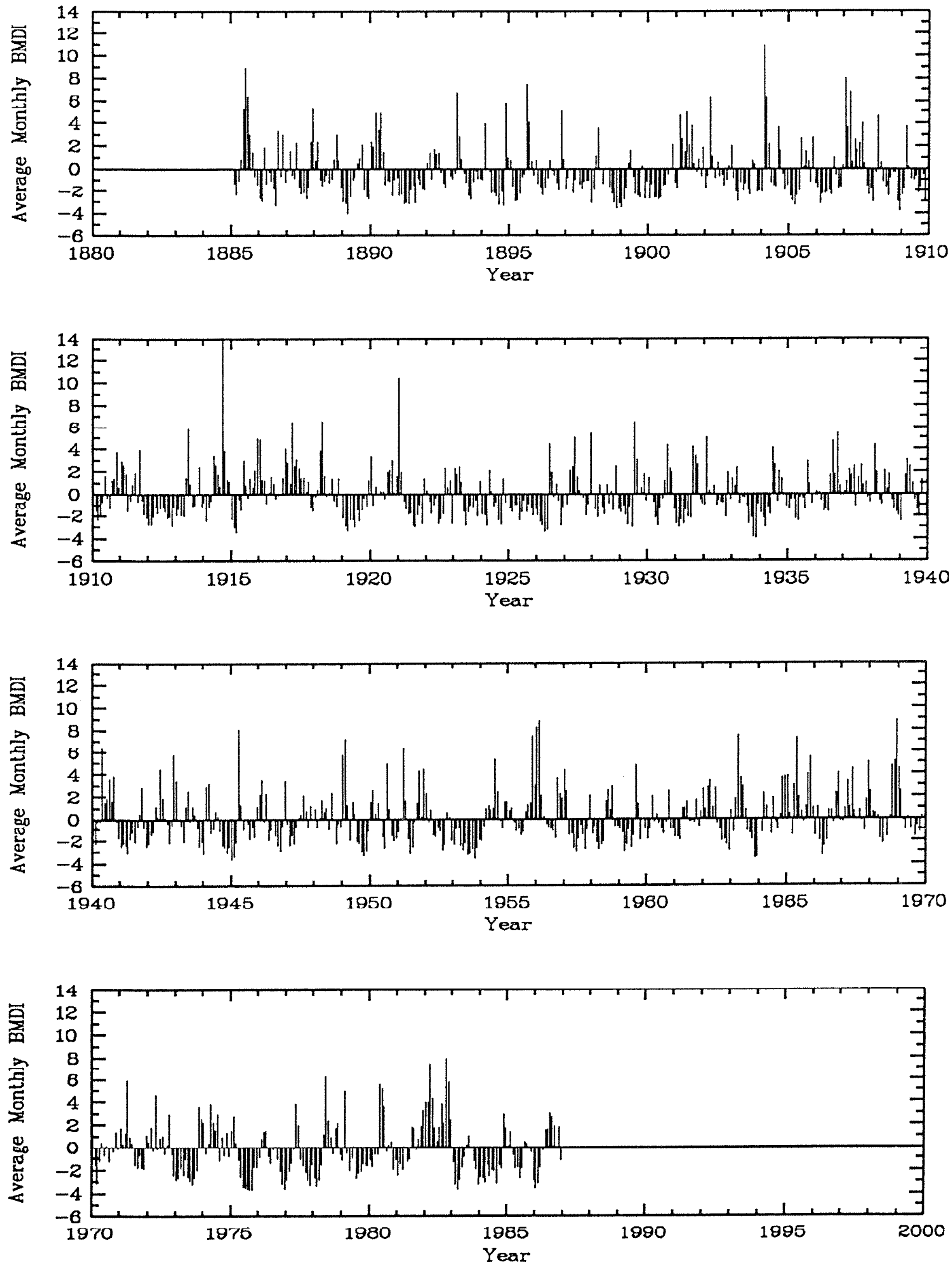
Appendix Figure D.9. Average monthly BMDI time series, Moloka'i Island



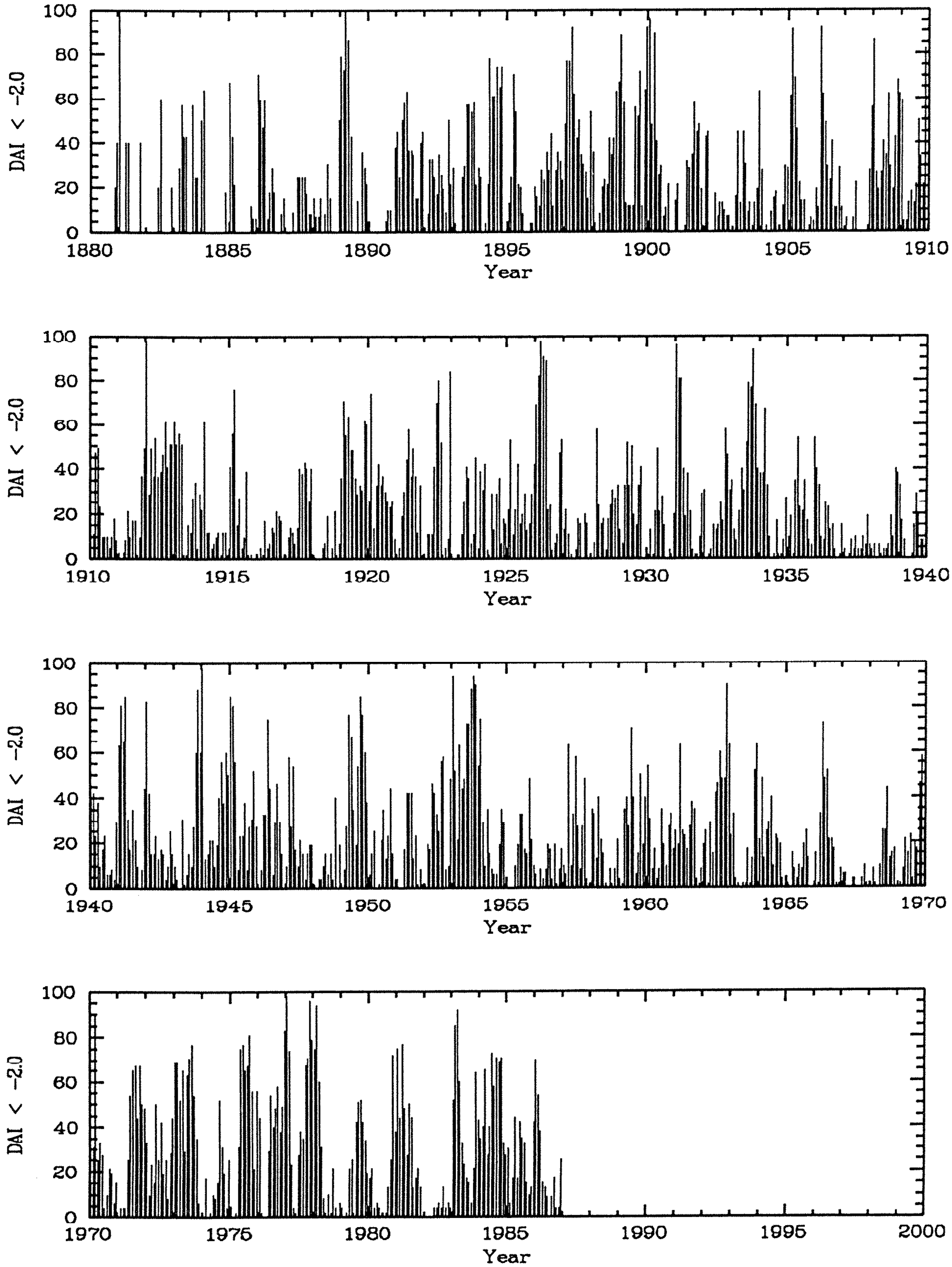
Appendix Figure D.10. Average monthly BMDI time series, Lāna'i Island



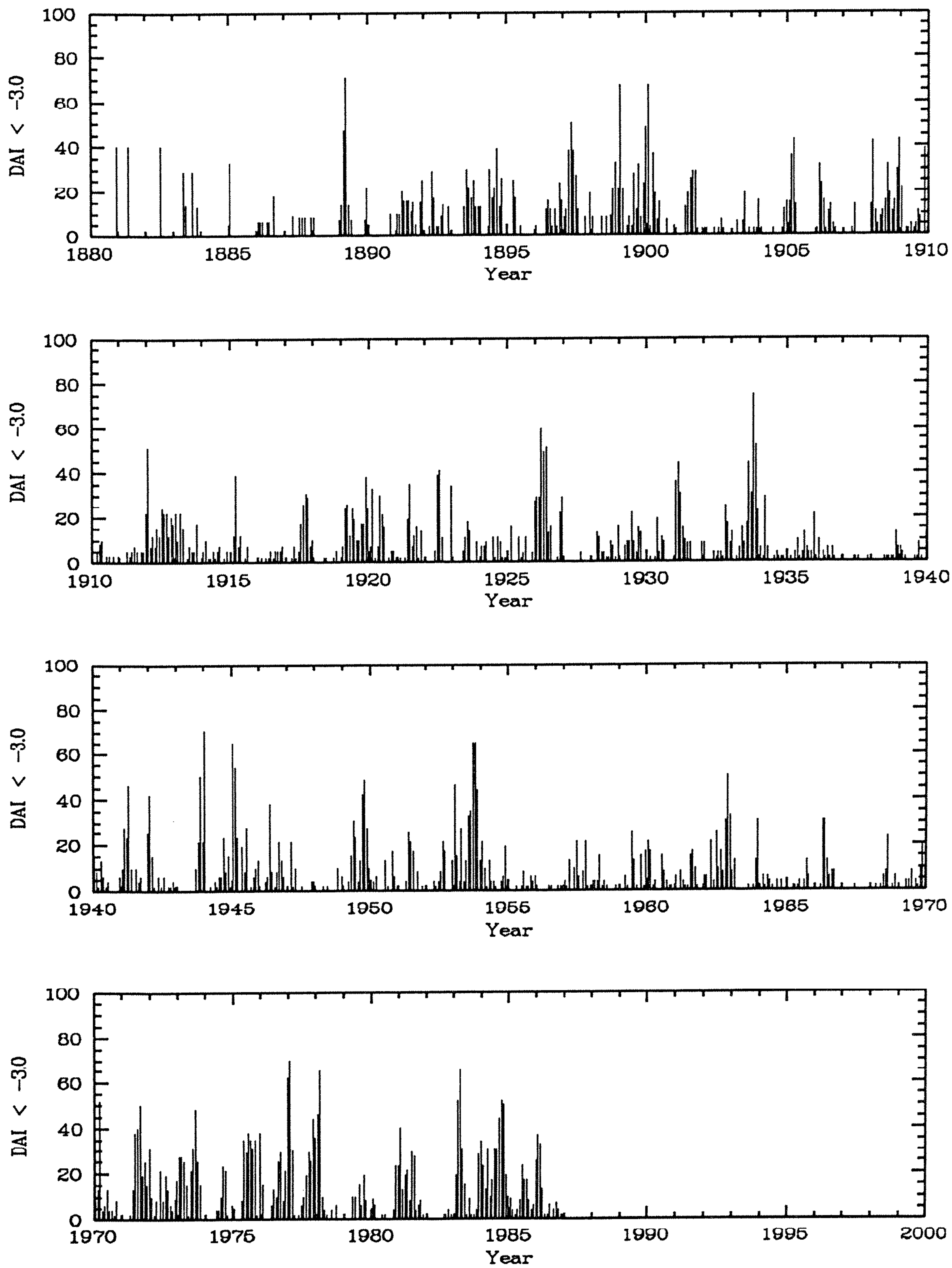
Appendix Figure D.11. Average monthly BMDI time series, O‘ahu Island



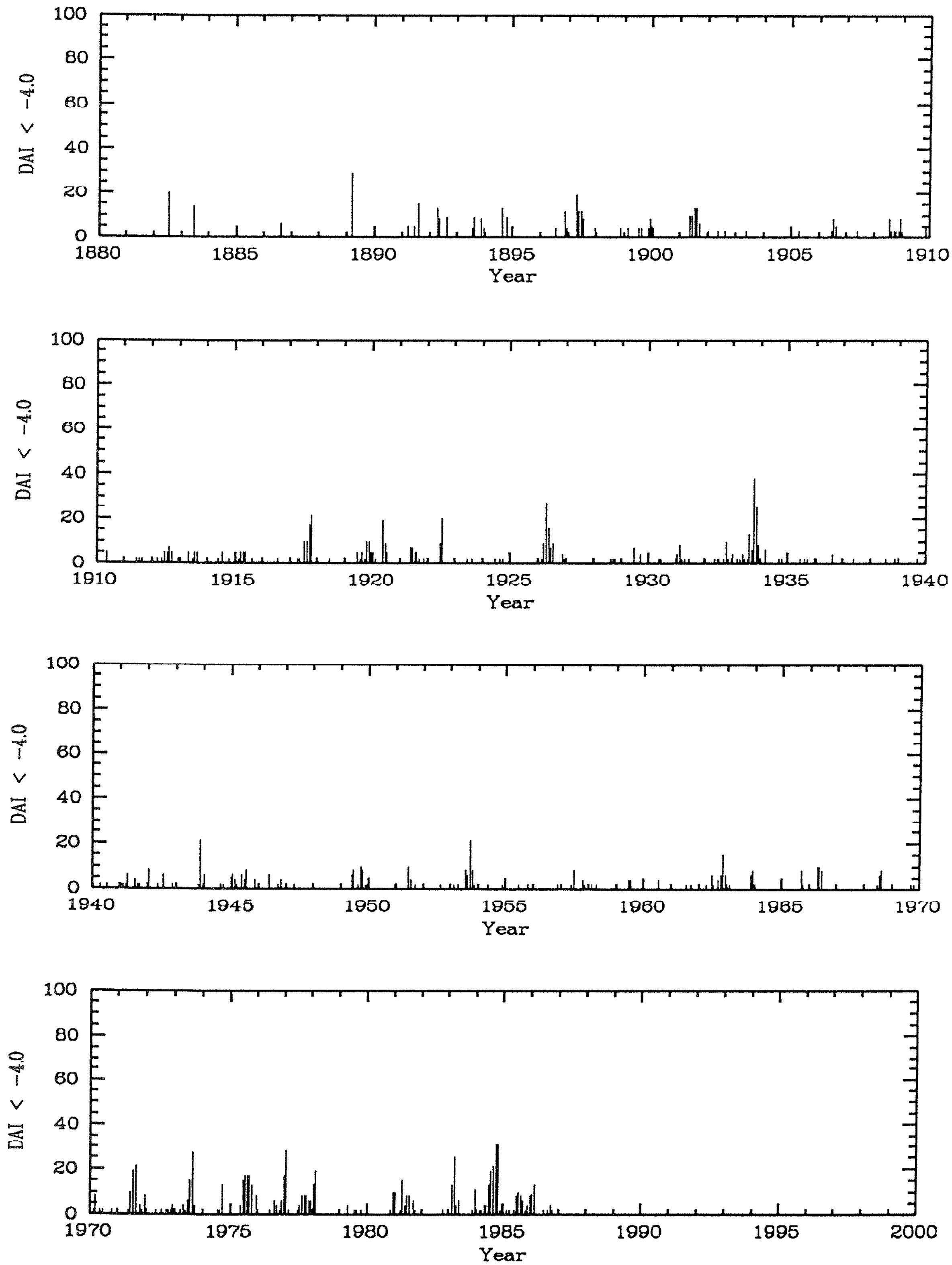
Appendix Figure D.12. Average monthly BMDI time series, Kaua'i Island



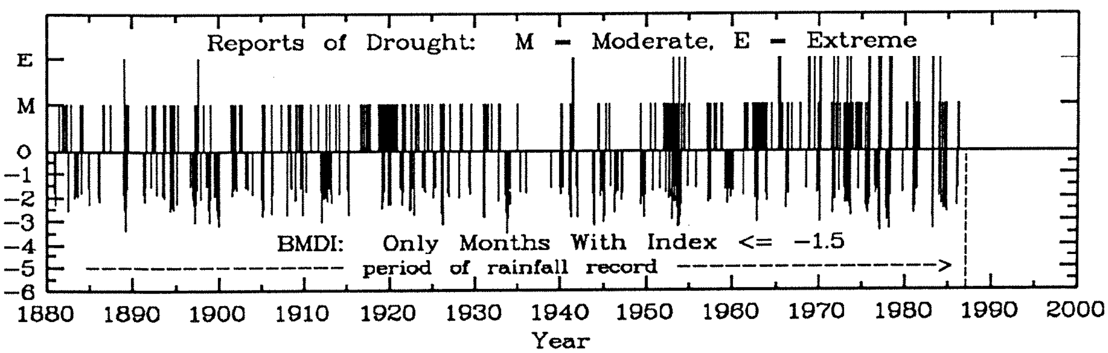
Appendix Figure D.13. Monthly Drought Area Index for moderate drought (% of rain gage sta. with BMDI < -2.0), Hawai'i State



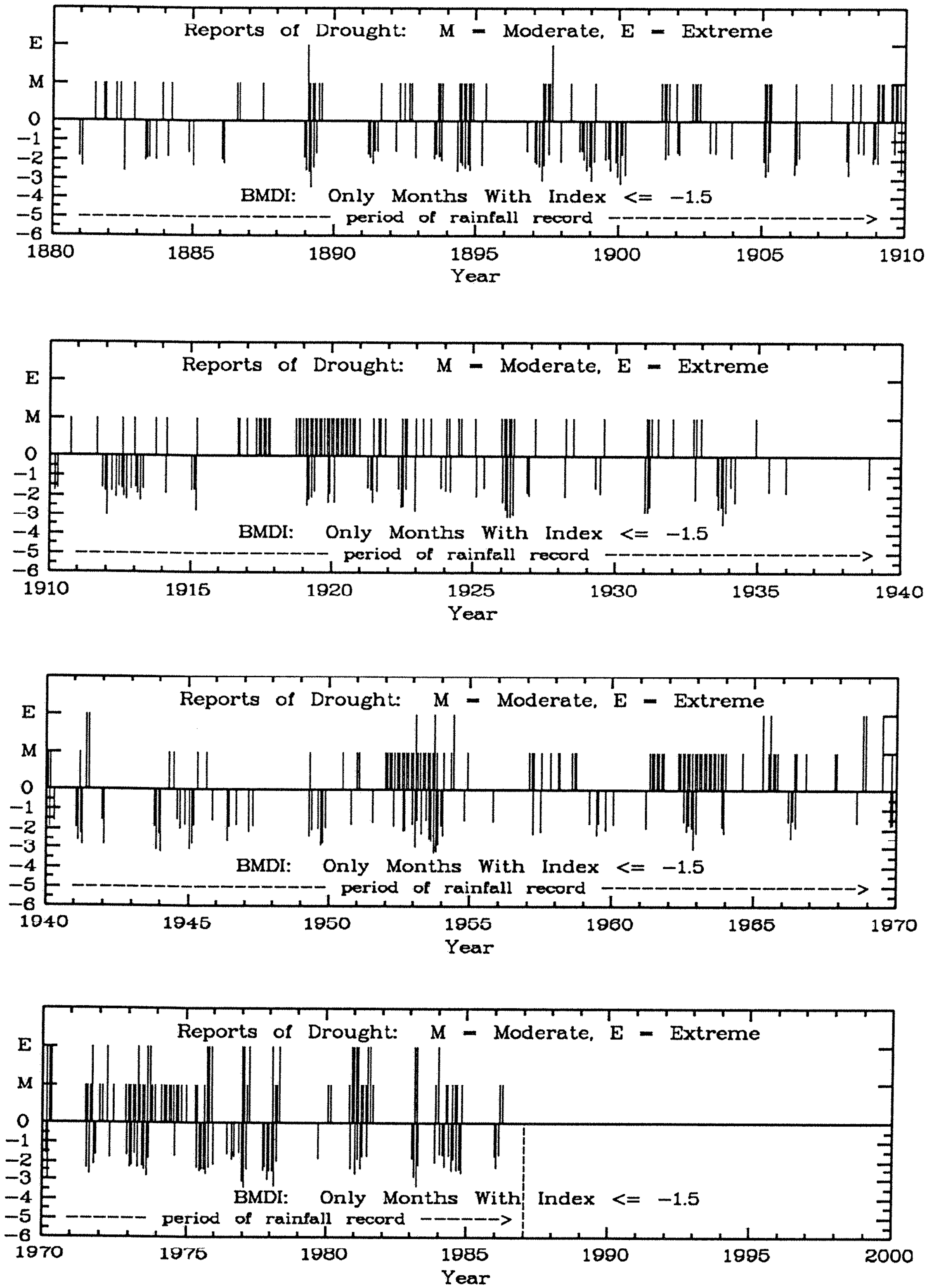
Appendix Figure D.14. Monthly Drought Area Index for severe drought (% of rain gage sta. with BMDI < -3.0), Hawai'i State



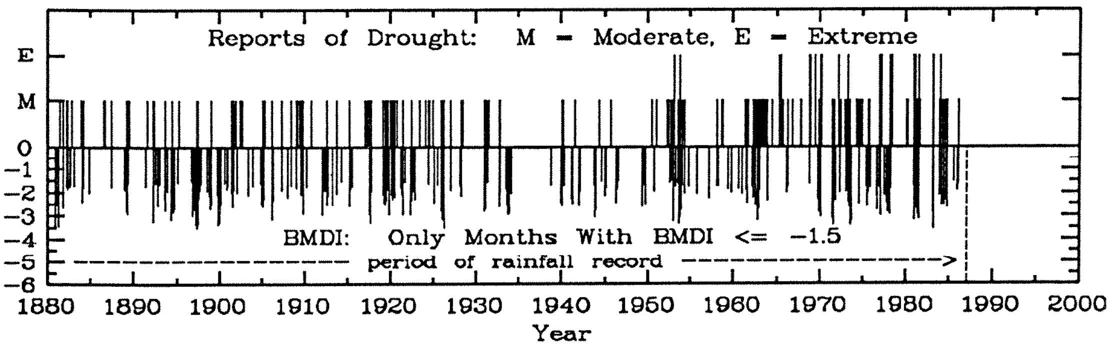
Appendix Figure D.15. Monthly Drought Area Index for extreme drought (% of rain gage sta. with BMDI < -4.0), Hawai'i State



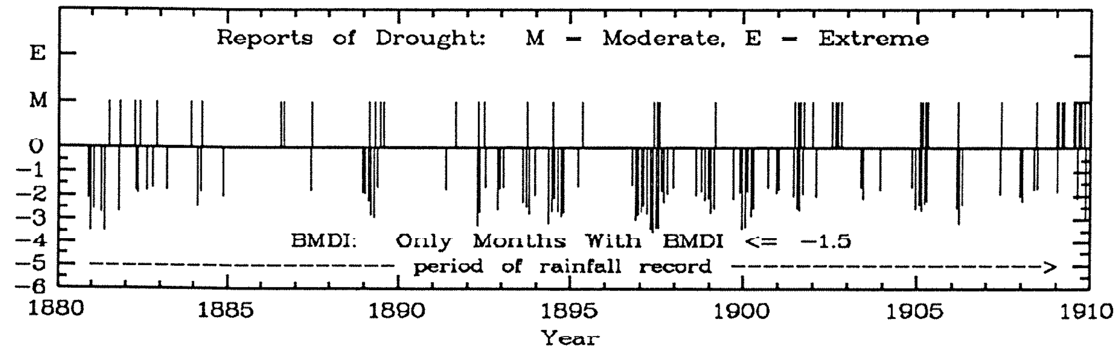
Appendix Figure D.16. Comparison, identified from descriptive accounts, with drought events defined by BMDI, Hawai'i State

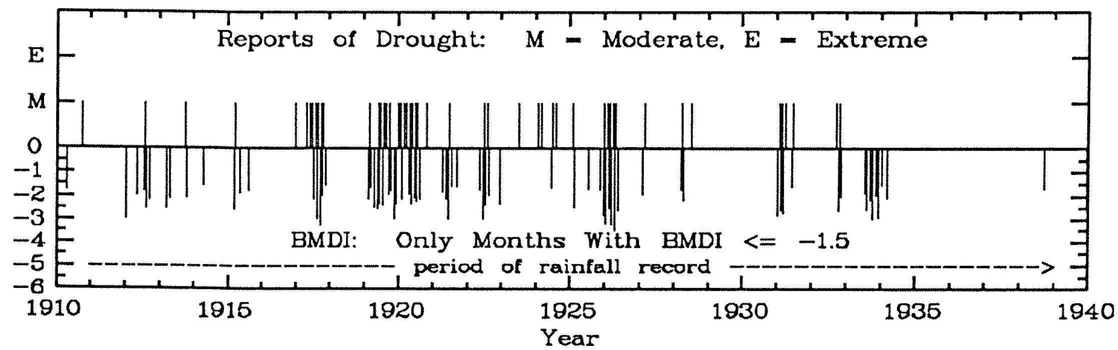


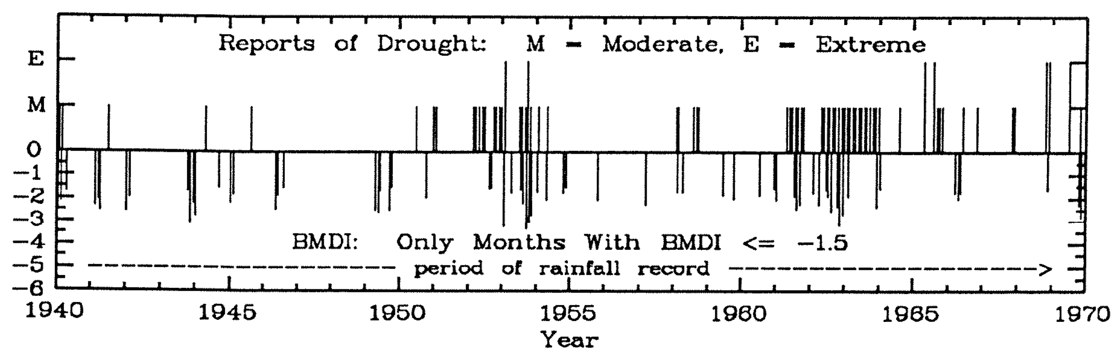
Appendix Figure D.17. Comparison, on expanded time scale, identified from descriptive accounts, with drought events defined by BMDI, Hawai'i State

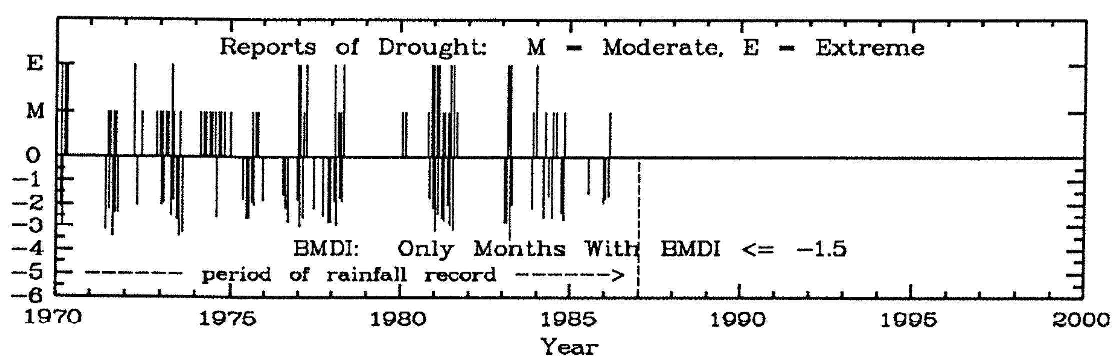


Appendix Figure D.18. Comparison, identified from descriptive accounts, with drought events defined by BMDI, Hawai'i Island

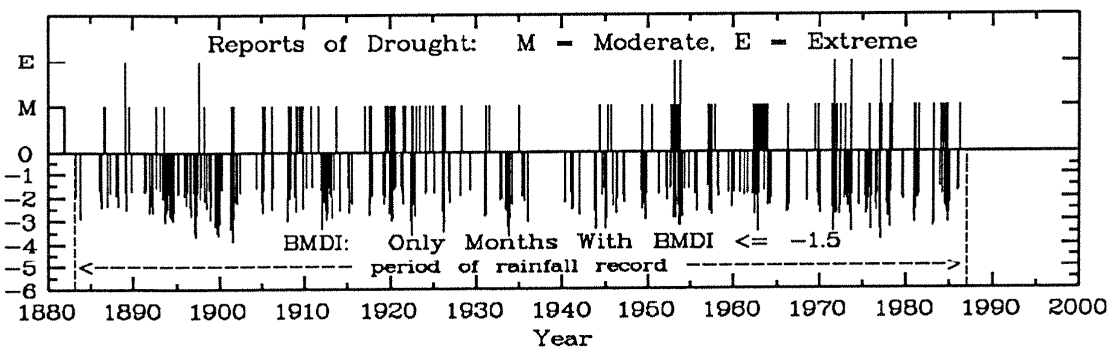




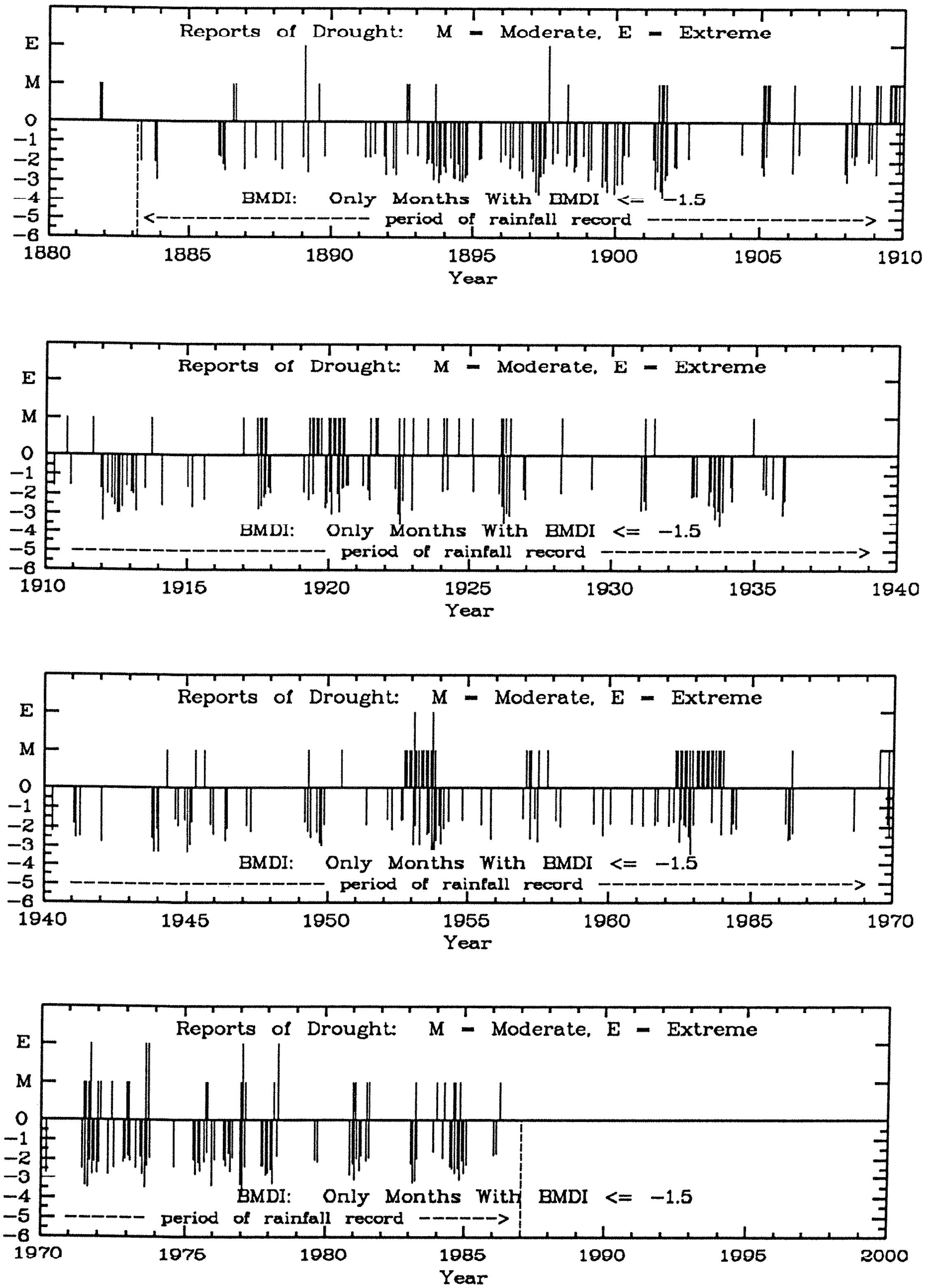




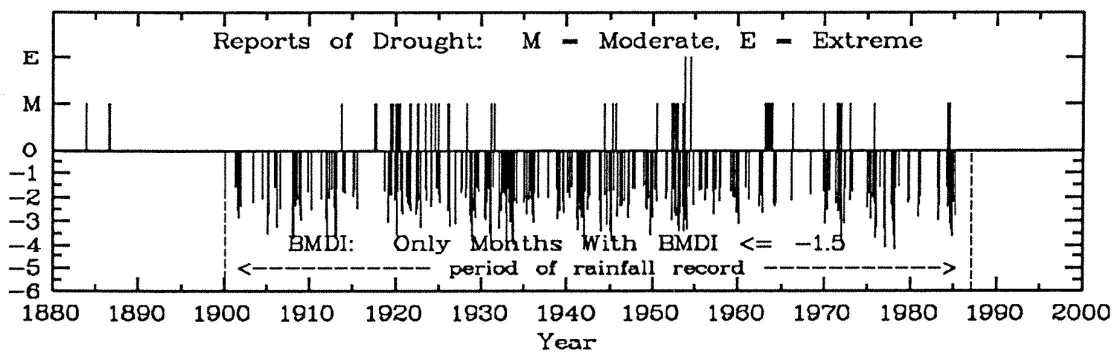
Appendix Figure D.19. Comparison, on expanded time scale, identified from descriptive accounts, with drought events defined by BMDI, Hawai'i Island



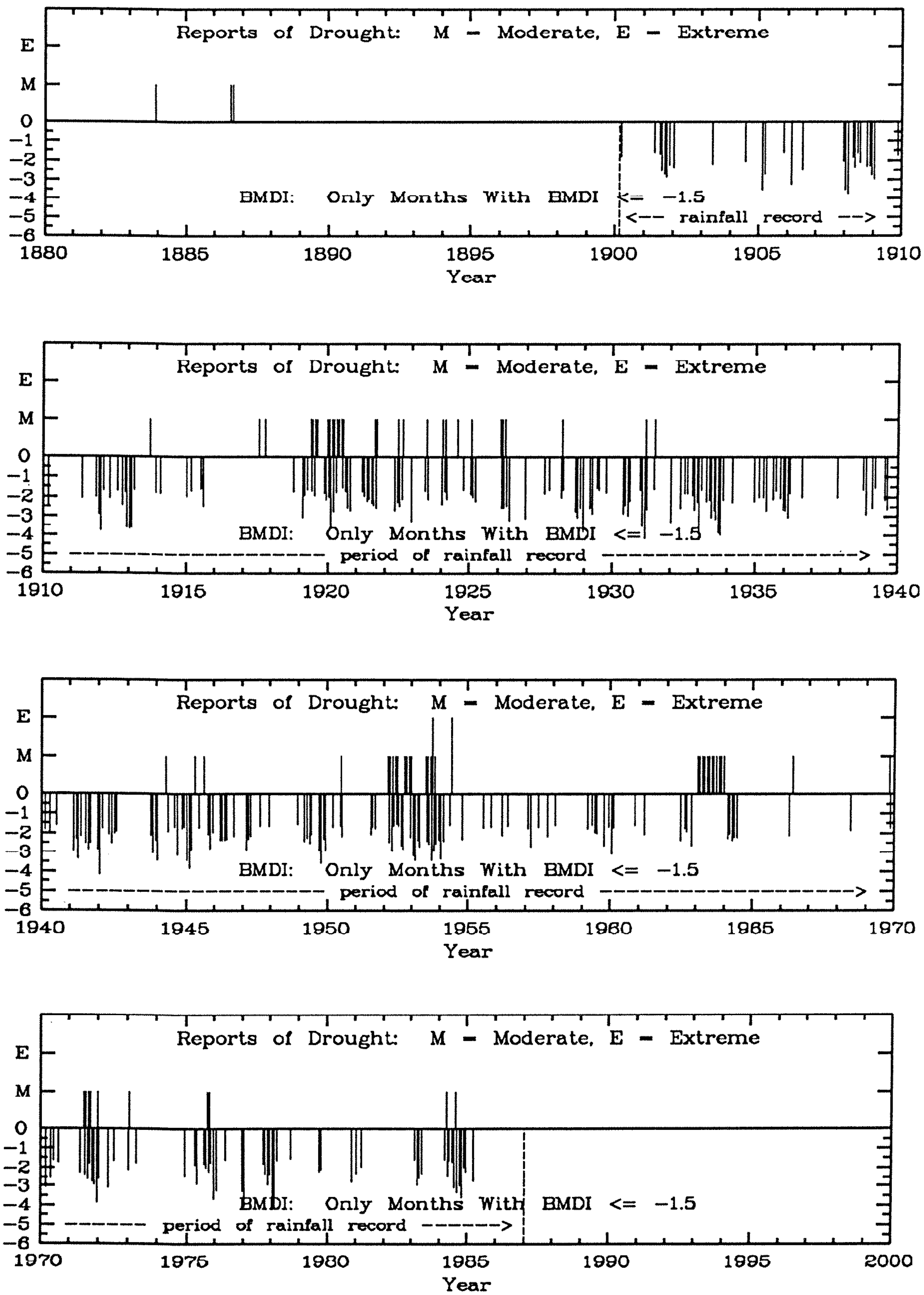
Appendix Figure D.20. Comparison, identified from descriptive accounts, with drought events defined by BMDI, Maui Island



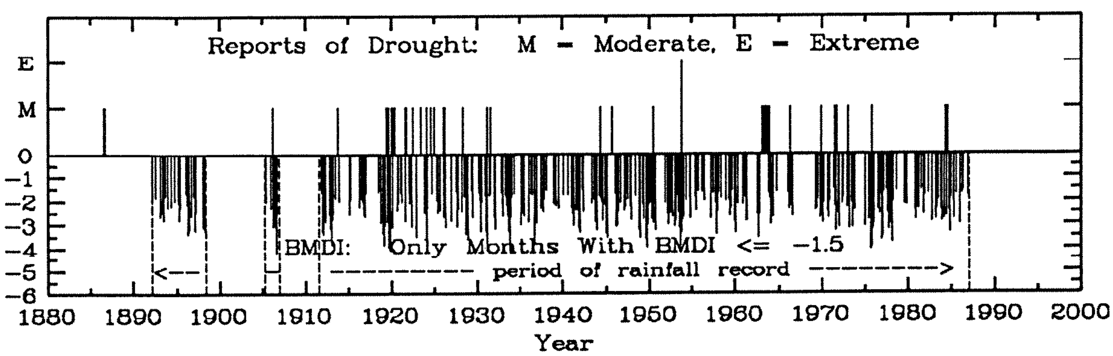
Appendix Figure D.21. Comparison, on expanded time scale, identified from descriptive accounts, with drought events defined by BMDI, Maui Island



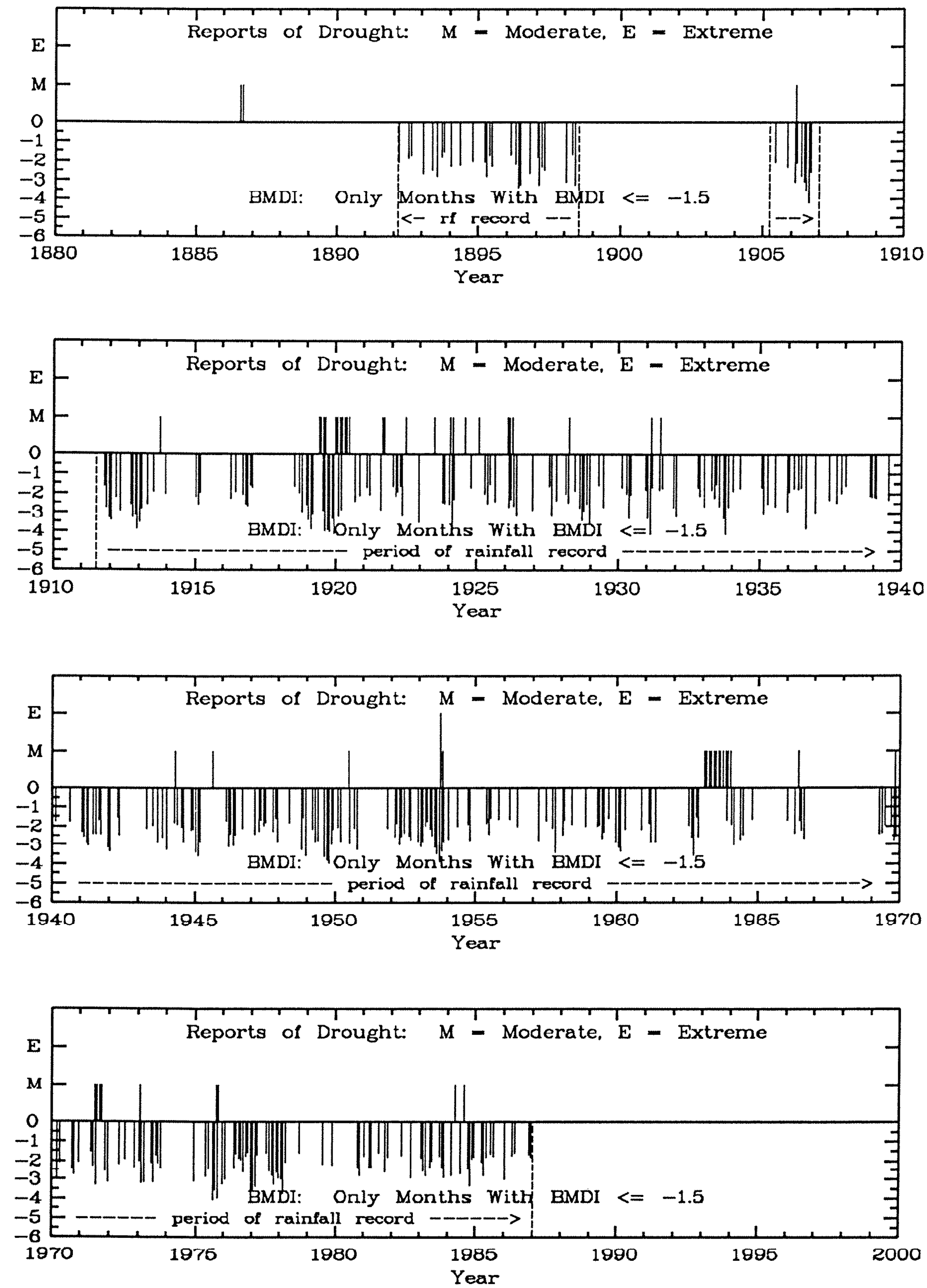
Appendix Figure D.22. Comparison, identified from descriptive accounts, with drought events defined by BMDI, Moloka'i Island



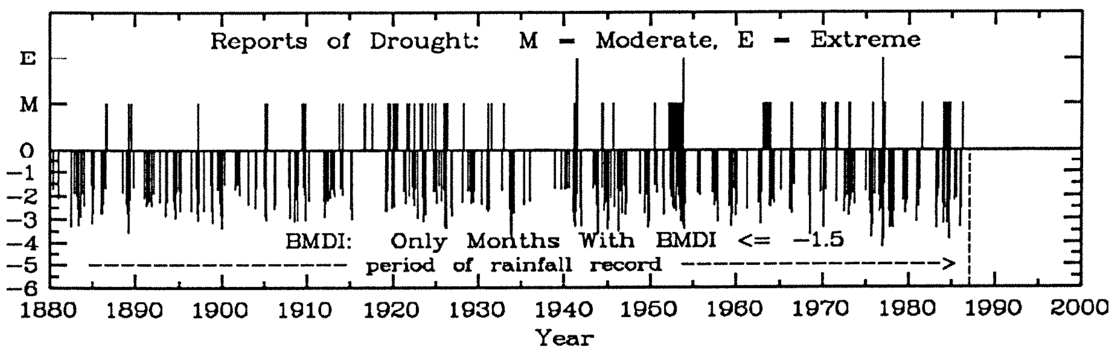
Appendix Figure D.23. Comparison, on expanded time scale, identified from descriptive accounts, with drought events defined by BMDI, Moloka'i Island



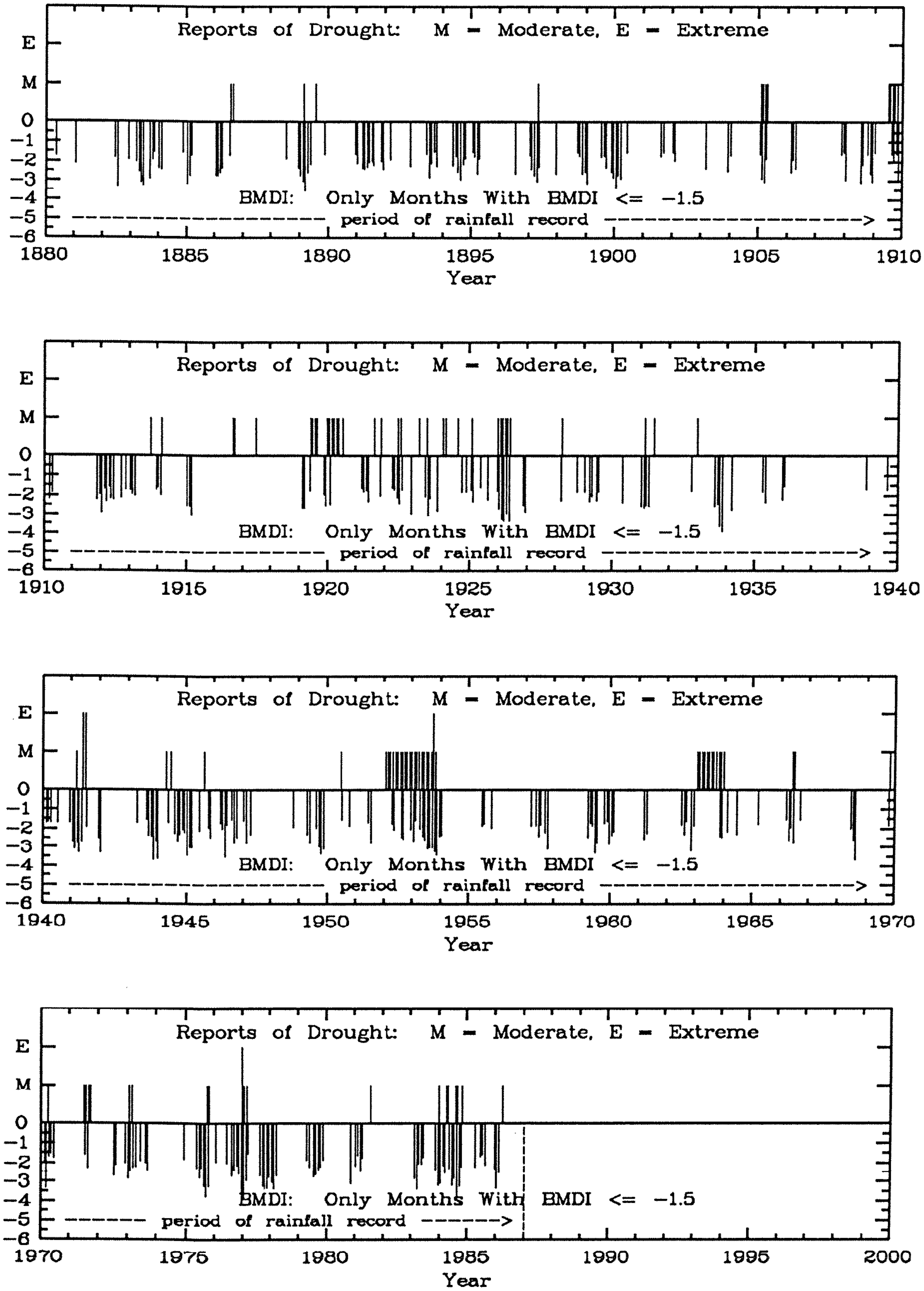
Appendix Figure D.24. Comparison, identified from descriptive accounts, with drought events defined by BMDI, Lāna'i Island



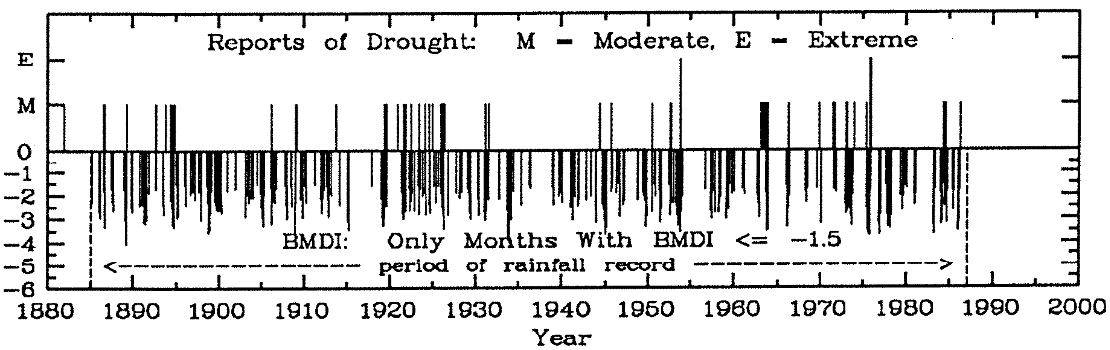
Appendix Figure D.25. Comparison, on expanded time scale, identified from descriptive accounts, with drought events defined by BMDI, Lāna'i Island



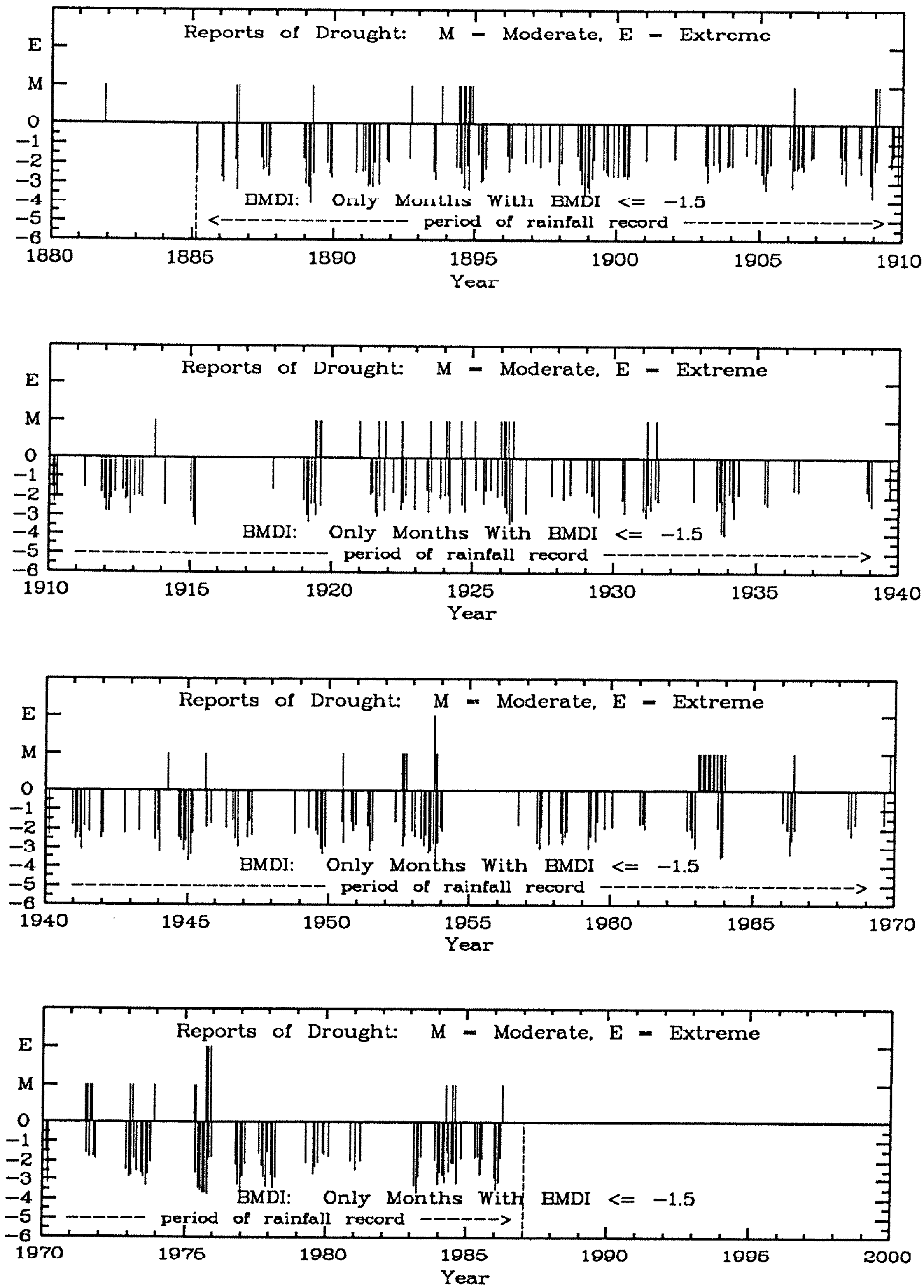
Appendix Figure D.26. Comparison, identified from descriptive accounts, with drought events defined by BMDI, O'ahu Island



Appendix Figure D.27. Comparison, on expanded time scale, identified from descriptive accounts, with drought events defined by BMDI, O'ahu Island



Appendix Figure D.28. Comparison, identified from descriptive accounts, with drought events defined by BMDI, Kaua'i Island



Appendix Figure D.29. Comparison, on expanded time scale, identified from descriptive accounts, with drought events defined by BMDI, Kaua'i Island